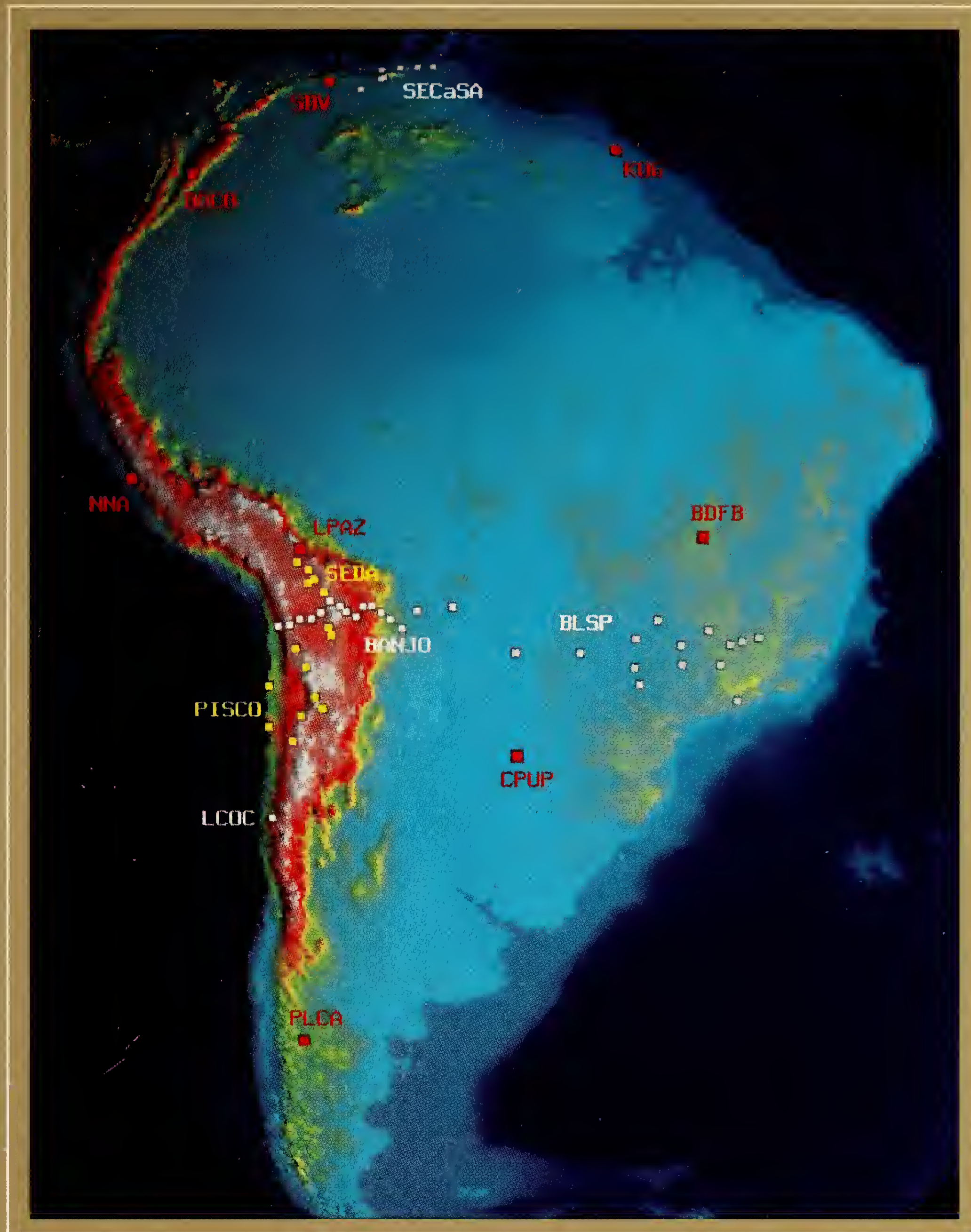

seismic stations in South America

Year Book 94

Carnegie Institution OF WASHINGTON

1994–1995

● astronomy ● plant biology ● developmental biology ● earth and planetary sciences ●

Carnegie Institution of Washington

OFFICE OF ADMINISTRATION

1530 P Street, N.W.
Washington, DC 20005-1910
(202) 387-6400

DEPARTMENT OF EMBRYOLOGY

115 West University Parkway
Baltimore, MD 21210-3301
(410) 554-1200

DEPARTMENT OF PLANT BIOLOGY

290 Panama Street
Stanford, CA 94305-4101
(415) 325-1521

GEOPHYSICAL LABORATORY

5251 Broad Branch Road, N.W.
Washington, DC 20015-1305
(202) 686-2410

DEPARTMENT OF TERRESTRIAL MAGNETISM

5241 Broad Branch Road, N.W.
Washington, DC 20015-1305
(202) 686-4370

THE OBSERVATORIES

813 Santa Barbara Street
Pasadena, CA 91101-1292
(818) 577-1122

—

Las Campanas Observatory
Casilla 601
La Serena, Chile

Carnegie Institution Web site: http://www.ciw.edu

Cover: South America offers rich opportunities for geophysicists studying the Earth's continents and lithospheric plates. Shown here, computer-generated map of South America and its continental shelf showing recent sites of seismograph deployment. The white BANJO, BLSP, and SECaSA arrays consist mainly of portable instruments belonging to Carnegie's Department of Terrestrial Magnetism (DTM). The observed data have been shared reciprocally with groups operating the SEDA and PISCO arrays. Shown in red are permanent stations of the global seismic network. LCOC represents a DTM instrument at Carnegie's Las Campanas Observatory, Chile. The work of the DTM seismologists and their colleagues has led to a succession of remarkable discoveries in the past two years.

The map was prepared by DTM's John VanDecar and Paul Silver. Colors show elevation. The height and breadth of the Andes reach a maximum near the pronounced bend of the west coast (Bolivian orocline). These features are consistent with models of continental and plate dynamics proposed by members of the DTM group. See essay by Silver in this Year Book, pp. 109–115.

Carnegie Institution

OF WASHINGTON

Year Book 94

The President's Report

July 1994–June 1995

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Administration and Trustees

PRESIDENT

Maxine F. Singer

[1] From November 7, 1994
[2] From December 12, 1995
[3] To October 6, 1994
[4] From March 8, 1995
[5] Died, September 9, 1995

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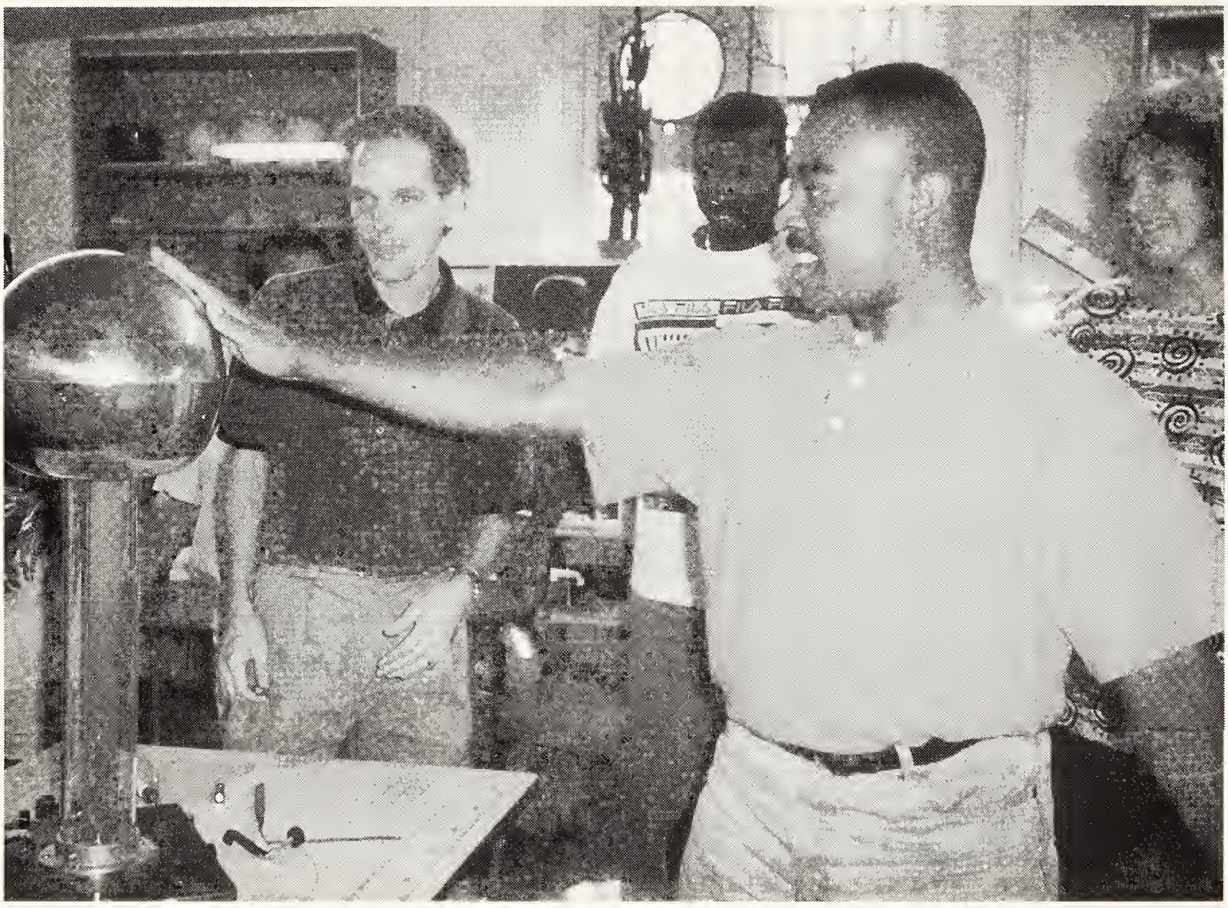
Under the original charter, from the date of organization until April 28, 1904, the following were ex officio members of the Board of Trustees: the President of the United States, the President of the Senate, the Speaker of the House of Representatives, the Secretary of the Smithsonian Institution, and the President of the National Academy of Sciences.

President's Commentary

Rotunda, Administration Building, Washington, D.C.



First Light director Chuck James, left, with teachers Jerome Thornton, Charles Mercer, and Marlene Piscitelli, learning about electricity at a 1994 session of the Carnegie Academy for Science Education (CASE). In CASE's second summer, 1995, one hundred elementary school teachers from Washington, D.C. public schools came to the Carnegie Administration Building to learn interactive teaching techniques for bringing science to children. Founded by Maxine Singer and funded by the National Science Foundation, the Howard Hughes Medical Institute, and other sponsors, CASE is led by Chuck James and Inés Cifuentes.

President's Commentary

And, after all, this is the point. What is truly amazing is the process, that we can use our minds to dare to comprehend the universe and our place in it. Yes, the story is grand, and everyone's first reaction is to feel small and unimportant. But the greatest wonder belongs to the one who wonders.

Alan Dressler
Voyage to the Great Attractor
Alfred A. Knopf, New York, 1994

The U.S. scientific community has been in turmoil since January 1995, when the newly elected Congress made plain its determination to decrease future federal deficits. Most scientists are sympathetic with the fiscal goals, but like other segments of the population, they prefer that spending cuts affect someone else. They are worried, and with reason. Among others, Daniel Kevles, a historian of science at the California Institute of Technology and a perceptive contemporary commentator, believes that we are experiencing a major readjustment of the U.S. science endeavor. He identifies the last such readjustment with Vannevar Bush's 1946 report, *The Endless Frontier.*

It is not surprising that *The Endless Frontier* often comes up as a benchmark in discussions of the present uncertainties. In several recent talks around the country, I too described the various challenges to scientific research as "in the wake of the frontier." Missing from my talks and the speeches and writings of others, however, is a description of the frontier itself. This is unfortunate, for it is impossible to evaluate the potential impact of major changes in what has been a highly successful scientific enterprise without a sound understanding of how science works.

Along with others, Carnegie tries to do its share of the needed explication. The Year Book annually discusses the pace-setting work of Carnegie Institution scientists in some of the fastest moving contemporary research areas. Scientists talk about timely subjects in layman's terms in our Capital Science Lecture Series in Washington. Magazines like *Scientific American*, newspapers, and television programs on public and Discovery channels also strive to bring current findings to a broad public. Rarely, however, does anyone try to explain to the general public what it's like to be on the frontier. What are the persistent considerations for scientists? How do they spend their time? How do they communicate with one another? What worries them? Why does their research require so much money? Much of this is beyond a short essay, but perhaps at least partial answers to such questions can emerge from a description of what concerns Carnegie Institution scientists.

Changing Ideas and Hypotheses

At the end of a hefty molecular genetics textbook that Paul Berg and I published a few years ago, we wrote that "almost nothing recorded in this book was known when we completed our formal educations over 30 years ago." The same can be said by any scientist who has been active for a lifetime in a lively field. Scientists are accustomed to rapid change.

Consider, for example, scientific models. A scientific model is in essence a detailed hypothesis describing a natural phenomenon, one consistent with all reliable experimental and observational information. Models are made for small, well-defined phenomena as well as for large, global ones. All new data must be critically examined and put in its proper place with respect to current models. If the new data are unassailable but don't fit, the model must be adjusted or perhaps even abandoned. Even the most cherished hypothesis must be scuttled as soon as a reliable experiment or observation demonstrates its falsity. Revision cannot be postponed until tomorrow, it must be immediate; if not, the scientist may waste time and money pursuing ill-conceived experiments of little or no significance. Scientists live with these circumstances although at times a scientist's ego is shattered along with a favorite hypothesis. Russell Hemley's essay (pp. 81–94) about recent work on

hydrogen at the Geophysical Lab gives a sense of how frequently scientists must confront changing ideas. The many surprises of late led to Hemley's title, "Hydrogen, Element of Uncertainty, Element of Surprise."

Public reluctance to overturn models is one reason why scientists are often impatient with popular perceptions of nature. For example, it is now almost two centuries since geologists like Hutton and Lyell recognized how ancient our planet might be, and more than a century since Darwin and Wallace showed how we might understand the history of life on Earth. Yet, people still argue about teaching these facts to schoolchildren in the U.S. and elsewhere.

Changing Methods and Instrumentation

Scientific methods and instrumentation now change rapidly. The experiments that surprised Rus Hemley and others were feasible because new technology made possible previously impossible measurements. Here, it was the Geophysical Laboratory's leadership in developing specialized synchrotron beamlines at the National Synchrotron Light Source at Brookhaven that opened new opportunities, as described in Charles Prewitt's essay (pp. 73–75). This theme, the interdependence of new science and new technology, emerges again in Sean Solomon's introduction to the material from the Department of Terrestrial Magnetism (DTM) (pp. 105–108) and in Wendy Freedman's elegant description of how modern

Participants at Carnegie's Institution-wide symposium on evolution, "From Galaxies to Genes: Evolutionary Processes," held at the Administration Building in October 1994 in honor of Carnegie trustee William Golden's 85th birthday. Clockwise from left: keynote speaker Elisabeth Vrba (Yale University), Paul Silver (DTM), Allan Spradling (Department of Embryology), Joseph Gall (Embryology), Thomas Urban (chairman of the Carnegie board), and Maxine Singer.

telescopes, including the Hubble Space Telescope, promise to yield the data required to solve major outstanding problems in cosmology (pp. 151–157). Biology too has become critically dependent on sophisticated instrumentation. Extraordinary new microscopes coupled to video cameras or computers yield three-dimensional pictures of living cells and reconstructions of intracellular structures that reveal fundamental properties. Machines that automatically sequence DNA segments or peptides, and computer software that provides access to and analysis of large international data banks, are essential to work in molecular biology on both animals and plants. Chris Somerville illustrates this in his introductory essay to this Year Book's text from the Department of Plant Biology. Even scientific book publication is enhanced by new technology, as we see in the extraordinary photographs of galaxies reproduced in the elegant new *The Carnegie Atlas of Galaxies*.

Modern instrumentation is as costly as it is marvelous. The future Magellan I telescope at Carnegie's Las Campanas Observatory in Chile is budgeted at a little over $40 million (and it is a tribute to Steve Shectman, Associate Director of the Observatories for the Magellan Project, and Marinus (Peter) de Jonge, the Magellan Project Manager, that, with about 69% of the budget spent or committed, the projection is within budget). In addition, each major auxiliary instrument for Magellan is likely to cost about $2 million—and three such are desirable at First Light, now planned for 1998. Accumulating DTM's twenty portable broadband seismometers over the last six years (described by Sean Solomon and Paul Silver, pp. 106–107 and pp. 110–111) required about $30,000 per instrument, while the ion microprobe that will be delivered to DTM late in 1995 will cost over a million dollars. The diamond-anvil cell so critical to the work of the Geophysical Lab at very high pressures is a rather simple instrument, but the gem-quality diamonds are expensive. And contrary to the advertisement, diamonds are *not* forever when they are subjected to several million bars of pressure.

For the most part, the days are gone when an individual scientist, even with the collaboration of talented engineers in well-equipped shops such as we maintain at Carnegie, could design and construct major apparatuses on their own, notwithstanding DTM's amazing and incessant reconstruction of mass spectrometers. Too many very sophisticated technologies

are now required. For example, Douglas Rumble at the Geophysical Lab, who is himself building a unique ultraviolet laser microprobe, must purchase some ready-made components and call on outside specialists for parts of the work.

Each new scientific discovery leads to new questions. But that alone would not make the frontier endless. Often, new questions can be engaged only after technological development opens a new window of potential. A classic example is Galileo's use of telescopes to demonstrate the ideas propounded by Copernicus and Kepler. Closer to home, and perhaps destined to be classic, are the new discoveries about hydrogen that depend on application of synchrotron radiation for analysis of material in a diamond-anvil pressure cell (see pp. 81–94). Another example is given in the essay in this Year Book by Robert Jastrow, Director of the Mount Wilson Institute, which operates the Mount Wilson Observatory (pp. 144–150). Jastrow explains the remarkable technique called adaptive optics and reminds us that it has been more than forty years since Horace Babcock, Director Emeritus of the Carnegie Observatories, proposed the concept. Yet, it is only now that the required technology is being developed, and it will be some time before it can be widely used.

The cyclical relation where science and technology promote one another is an important part of the continuing change at the frontier. The cycle will turn as long as society allows for human imagination and inventiveness. However, as John Ziman, a British scientist and sociologist of science, points out in a recent book about the current transitions in the scientific enterprise, the cycling now "has begun to spiral wildly outwards in scope and scale."* Consequently, the costs of providing the increasingly complex instruments for research are growing. We feel these pressures acutely at the Carnegie Institution, as I wrote earlier. Moreover, the need for new instruments will be with us as long as the Institution's goal is excellent, original, innovative research. We need to be prepared to spend annually several million dollars on instruments and associated facilities, outside of our normal operating budget. General economic inflation is partly responsible for the high costs, but the main culprit is the increasing capabilities and sophistication of the instruments themselves.

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*John Ziman, *Prometheus Bound: Science in a Dynamic Steady State,* Cambridge University Press, 1994, p. 44.

Facilities

From its beginnings, the Carnegie Institution was committed to providing modern facilities for its scientists. In the century's first decade, fine architects were engaged to build landmark structures to house DTM, the Geophysical Lab, the Observatories, and the administration. In time, outstanding research facilities were constructed for Plant Biology (1928) and Embryology (1963). These assets served for many years without major new construction.

Scientists become attached to their work places, especially if those places have historical significance to their field. They come to love their familiar surroundings, antiquated electrical systems or not. Their attachments to aging buildings can carry the day even as the inadequacies grow with the decades. Minor additions, repairs, and renovations can make the situation marginally acceptable. But such places are really inadequate for modern research by newer generations of scientists. The commitment of an institution having shabby labs is questionable.

In the past seven years the state of our facilities has changed. The plan to construct a modern research building for joint use by DTM and the Geophysical Lab, and to renovate DTM's original main building and the cyclotron building at Broad Branch Road was initiated by James Ebert, then president of the Institution. The project was completed in early 1991. Since then, department scientific staff, working with architects and professional project managers, have planned and completed building projects at the other three departments. A new addition was made to the facilities of the Department of Plant Biology, increasing its space by 78%, or 13,235 square feet. In two separate projects, in 1989 and 1995, the Department of Embryology modernized and extended its laboratories and added common space by imaginative use of its roof; this year the W. M. Keck Foundation Laboratory for Vertebrate Development was opened. And in 1994, the Observatories replaced old and earthquake-damaged space on Santa Barbara Street with a new structure housing a lecture hall, conference room, and expansive shops for work on instruments; what had been a parking lot and a jumble of machine shops is now a pleasant campus. Work on the modernization of the remaining buildings at Santa Barbara Street, including the original department headquarters, the historic

The W. M. Keck Foundation Laboratory for Vertebrate Development was built on the second floor of the Department of Embryology.

Myron Hunt Building (named for its architect), is now planned. The Santa Barbara Street location, the site of the Observatories' headquarters since 1905, has a legendary character for astronomers; it has been home to such giants as George Ellery Hale, Edwin Hubble, and Walter Baade. Even Charles Richter (of the Richter scale) worked there for a while.

Contemplating these completed projects elicits an institutional sigh of relief. At least the major facilities requirements are resolved for the next 5–10 years. But like everything else in science, facilities cannot remain static. They require reshaping and rewiring if they are to be appropriate for new research efforts, and this must be an ongoing activity. The new ion microprobe for DTM offers a good example. The machine needed a spacious and protected environment. How could that be found at Broad Branch Road, where even the ample new space was already "owned" and jealously guarded? Sean Solomon's description (pp. 107–108) telling how this problem was solved is a familiar Carnegie tale of ingenuity, self-sufficiency, and frugality. To call this a "do-it-yourself" effort would be to demean the talents of Mike Day and his associates on the Broad Branch Road staff. It would also hide the fact that the project required money. Incremental funds, outside the regular operating budget, will almost always be needed for such projects, although in this case DTM cobbled the money together from savings and the sale of the old cyclotron iron as scrap.

People

Instruments and facilities are important only if they are in the service of imaginative, rigorous, and hard-working people. Excellent people—scientists and support staff—are really the main point, people who are flexible, who change ideas, methods and approaches as science changes. To sustain frontier research

over a lifetime is a unique challenge. The inclination to pursue the comfortably familiar, long after that approach has worn itself out, must be fought. Tantalizing models must be suspect if the methodology and instrumentation necessary to test them simply do not exist. Kip Thorne, a Caltech astronomer, asks a question: "Why do we physicists think we know the things we think we know, even when technology is too weak to test our predictions?"* Other scientists consider such knowing very provisional indeed. Each scientist struggles with such problems at critical junctions in her or his life. Each department director must be aware of these struggles and be prepared to help, to listen, to advise, to evaluate.

There are additional reasons why the appointment of department directors is the most important and most challenging of the Carnegie president's tasks. Traditionally, department directors serve long terms, and each tenure often marks a change, albeit slow and subtle, in the department's research directions. This is accomplished neither by fiat, nor by requiring all staff members to fit their research to the director's interest, nor by trying to repopulate the department with those doing the most fashionable work. Rather the change comes from perceptions of which research areas are likely to be most exciting in the future. It is also driven by what interests the very best young scientists, because it is they who will make the giant steps in the coming years. To provide the needed leadership, the director must be a distinguished scientist of substantial accomplishment with ongoing research programs. In addition to all this, a director is the advocate, to the president, for the department's share of institutional operating funds and private grants. And when funds are apportioned, it is the director's responsibility to decide how to use them and to monitor expenditures so that the department operates within its budget.

The final challenge is to identify a person who recognizes that first and foremost, scientific leadership means serving the interests of the staff. In four of the five departments, new directors have been appointed in the last seven years. The president in each case sought the advice of trustees and scientists within the department and elsewhere, usually through a search committee. In some instances it seemed best to choose the new

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*Kip Thorne, *Black Holes & Time Warps: Einstein's Outrageous Legacy*, W. W. Norton & Co., 1994, p. 17.

director from the ranks of the department's staff; in others, the president concluded that it was advisable to recruit a person from outside Carnegie.

For department directors, the appointment of a new staff member is a critical responsibility. There are few guidelines for identifying the right individual. How can one predict which of the most promising candidates will sustain her or his promise long into the future? Brilliant young scientists often burn out early. Yet in identifying individuals offering the greatest promise of breakthrough research, Carnegie almost always decides upon newly independent investigators rather than senior people with established reputations. Our underlying assumption is that new staff members will spend their remaining careers at Carnegie. More often than not, this is what happens. Occasionally, a staff member leaves to join another institution. And even more rarely, a scientist may be asked to go elsewhere; Carnegie Institution does not grant tenure, so there are no administrative barriers to asking someone to leave.

Recruiting the most promising scientists is a highly competitive enterprise, even these days when there are hundreds of applicants for each job. Carnegie's competitors are the major research universities. In some ways, we offer very little in comparison: no tenure, low salaries, few if any students, little or no opportunity to teach, none of the amenities of large campuses. But our traditions of independence and substantial institutional support seem to carry the day for some very desirable and adventurous people. Here the director and staff play a critical role in conveying to the candidate the advantages of a collegial community and the Institution's commitment to risk-taking.

Finding the Resources

All of us, scientists, staff, trustees, and administrators alike, are committed to the long-term viability of our Institution. The excellence of Carnegie research and the independence of the Institution are implicit in our definition of viability, as is our dedication to fundamental research. How can we sustain this?

The Carnegie Institution is known in the scientific community for its frugal habits. Time and again, visitors are astonished at how much fine science is accomplished within our limited annual operating budget. They are also surprised to learn how small the

Institution is, in view of the impact of its scientific work. These two Carnegie fundamentals—frugality and small size—have stood us in good stead and should be maintained.

The Institution depends on its endowment for the bulk of annual operating funds. Unlike most large research universities and small independent research institutes, and by design, only 30 percent of operating funds come from federal grants. This helps assure independence, but it also means that increasing the endowment by sound reinvestment of earnings and new donations is essential for the future. About four years ago, we adopted a newly stringent approach to annual spending from the endowment. The rewarding results are apparent in the steady rise of the endowment value recorded in the financial statements at the end of this volume. Thus our long-term prospects are much improved albeit at the expense of some current ambitions. We have scrimped on salary raises for scientists and staff, we have canceled subscriptions to journals that should be in our libraries. The department directors, who must deal with such rigors on a daily basis, bear the responsibilities for operating within restricted budgets. Their responses have been straightforward, cooperative, and collegial. In this, they reflect the good will and institutional dedication of the departmental staffs. But the directors also recognize that the departmental sacrifices, should the stringency continue or deepen, will stand in the way of our scientific goals. The steady improvements in the endowment value give promise that such will not happen. Besides the austere spending, the endowment outcome reflects the dedicated expertise of the Finance Committee of the Board of Trustees and the generosity of trustees and friends.

Another consequence of our stringent endowment spending is an increased dependence on private philanthropy and federal grants (30 percent is significantly higher than earlier years' federal support). Carnegie's trustees are the mainstay of our private philanthropic support of the research. Not only are the trustees generous, but their generosity encourages private foundations. In our favor too are the substantive relations between our scientists and the staffs of foundations that have been developed by the Director of Institutional and External Affairs. We learned this year, from a survey published by the *Chronicle of Philanthropy* (May 18, 1995), that we ranked fifth nationwide (in 1993) in the dollar value of foundation support

among institutions classified as "science" (and excluding universities).

The operating funds obtained through federal grants support the costs of specific research projects proposed by staff scientists. These help pay the costs of materials, travel, publication, and stipends for young postdoctoral scientists. At Carnegie, they contribute only minimally to staff salaries, less than 10%. Separate federal grants have been available, through peer-reviewed programs, to assist in the acquisition of instruments. Nationwide, the total of such federal funds doesn't approach what can be justified to maintain the U.S. lead in science and technology. And it is likely that substantially less will be available as the government strives to correct its own budgetary problems. But for excellent scientists with innovative ideas, there has been, up to now, a reasonable chance for support. The Institution has indeed obtained a fair share of the available funds relative to its small size, despite the widespread myth that we are a wealthy institution. For example, the full cost of a new DNA-sequencing machine at Plant Biology was obtained through a grant to Chris Somerville from the Department of Energy. Douglas Rumble (Geophysical Lab) and Erik Hauri (DTM) obtained 50 percent of the costs of the UV-laser microprobe and the ion microprobe from the NSF. Almost always such grants require that the Institution provide matching funds, and we do this through a combination of gifts from individuals and private foundations as well as institutional resources.

Carnegie scientists appreciate their advantage over university colleagues, who depend much more heavily on external funding. They likewise understand the expanded opportunities provided by federal grants. But they are also sorely aware of the large investment of time required for the preparation of competitive proposals. Federal support entails substantial costs in time and effort. Frequently, multiple redundant proposals to different agencies are necessary to improve the chances for success in the face of limited federal or foundation budgets and competition. Each proposal is a hefty document. The usually anonymous reviewers who rate proposals for federal agencies look for originality, potential for success, detailed planning, and comprehensive knowledge of the relevant scientific background. Sometimes, irrelevant academic policies and biases intervene. Often young, unproven investigators are at a disadvantage. The

federal agencies themselves want tangible results and thus generally avoid the larger risks associated with highly innovative ideas.

Changing Traditional Practices

Over the long term, Carnegie's traditional approaches for organizing research and obtaining adequate resources cannot sustain the quality of the scientific effort to which we aspire. This is the hidden text of the preceding discussions of instruments, people, and facilities. New approaches will be required by Carnegie and by other research institutions as well. For example, one important mechanism for assuring access to sophisticated, state-of-the-art instruments will be through cooperative efforts with other institutions. This is the concept underlying our proposals for a second Magellan telescope. The total estimated cost of twin 6.5-meter telescopes at Las Campanas is substantially less than twice the cost of one. The scientific advantages to ourselves and the partners we seek for this venture would be enormous; the disadvantages will include some modification of the now unstructured but efficient ways that the Las Campanas Observatory is managed, as well as the need to accommodate the requirements of an expanded community of astronomers.

Erik Hauri's successful grant proposal to the NSF for the ion microprobe included a plan for sharing the instrument with other mid-Atlantic institutions which will contribute to the maintenance of the microprobe or to the required matching funds. This will extend the potential for cutting-edge research. It will also bring new colleagues and their students along with their different ideas to the Institution. Some disadvantages are also apparent. Hauri will have to spend significantly more time managing the facility and teaching than if DTM had exclusive use of the instrument. Wear and tear on the microprobe will be greater, and maintenance time and cost will probably increase. Other advantages and disadvantages will emerge once the microprobe is in operation. In any case, this plan (like the Magellan partnership) marks a significant shift from customary Carnegie operating habits. Young scientists, especially, appear willing to make such compromises, assuming a high return. But these individuals joined Carnegie at least in part because they found our traditional independence attractive. We will have to

Artist's rendering of the Magellan I and II telescopes at Carnegie's Las Campanas Observatory, Chile. (T. Asa Bullock, L&F Industries.)

work hard to optimize the new arrangements.

It was the Carnegie Institution itself that initiated the ion microprobe and Magellan II proposals, and in both projects, Carnegie scientists will retain considerable control. Other cooperative efforts are planned and carried out upon external initiatives by, for example, the National Science Foundation or consortia of research institutions. The Center for High Pressure Physics, a joint effort by the Geophysical Lab, Princeton University, and the State University of New York at Stony Brook, is sponsored by the National Science Foundation. After five years of operation, it appears to be successful; the Geophysical Lab's scientists have not been constrained in the independence of their research. Nevertheless, it is difficult to estimate the indirect effects of this arrangement. Perhaps Geophysical Lab scientists put some new ideas aside because of the ready availability of Center funds.

Changing Rules and Expectations

Everyone in the scientific community recognizes that Daniel Kevles and John Ziman are correct: the framework for scientific research is changing. There are clues around us that suggest the meaning of these changes, but no one can interpret them reliably. Some politically powerful people express deep understanding of the significance of fundamental research for the future of our country and the world; others seem to have little or no appreciation for the vital role played by science in modern life. All these individuals are, however, dedicated to controlling the nation's deficit. Some argue that American industry will fill the gaps in support of basic research—but anyone who has tried to

raise funds from industrial sources or has talked with corporate leaders knows that the available resources are very limited. Industrial support is obtained at some research institutions and universities, but it is for research in the interest of the industry, not to allow for the original ideas of excellent and independent scientists. Such academic/industrial collaborations are also promoted as a way for academic researchers to contribute to the immediate national interest of improving U.S. competitiveness. Such arrangements are not for Carnegie.

Indeed, it is perhaps more important now, in this changing environment, than at any time since the publication of *The Endless Frontier* for the Carnegie Institution to remain committed to its fundamental principles: to foster fundamental research and the unique individuals who have the talent and motivation to pursue it, and to do so in ways preserving the independence of our investigators. We will need to be clear about those elements of our traditional ways that are vital for our goals, as we define them. We will need to be equally clear about those habits which are not central to our goals and be willing to change them. In this way we can make unique contributions to our nation's and the world's future.

Standing firm on our commitment to independent, fundamental research will not, however, be sufficient. If we are to continue to attract federal and private support for new projects, instruments, and facilities, we will also need to respect the nation's desire that science demonstrate its willingness to contribute to contemporary national needs. The way to do this without compromising our institutional principles is to continue to concern ourselves with science education.

The Institution has always been active in the advanced education of professional scientists. Extending this concern to primary and secondary school science education is a natural way for us to contribute to one of the nation's clearest needs, and is consistent with our goals and traditions. First Light (the Saturday science school for children at the Administration Building), the Carnegie Academy for Science Education (CASE, the training program for Washington, D.C. elementary school teachers), and the Capital Science Lecture Series (for the general public in Washington, D.C.) are already substantial projects, largely funded by philanthropy and federal grants. The Department of Embryology in Baltimore has long worked with Baltimore high

school teachers. A large group of high school and undergraduate student interns did research at the Broad Branch Road campus in Washington this last summer, and they presented their work to their colleagues at an end-of-summer symposium. Efforts in science education will soon extend to Chile, where Las Campanas has long benefited from the cooperation and hospitality of the Chilean government and universities; with the help of the Fundación Andes and private donors, a summer astronomy school for Chilean students interested in physical sciences will be initiated next year.

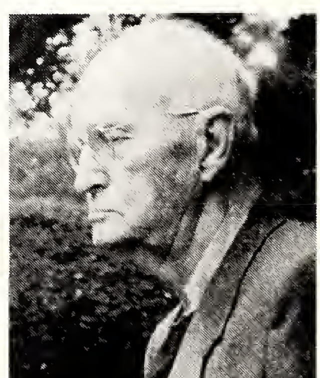
All these activities are in our own interest as well as those of the more general society. The "endless frontier" moves rapidly, and scientific understanding of the natural world is moving further and further from notions prevalent among the general public. If this troubling discontinuity is to be ameliorated, the gap between the frontier and the general public must be narrowed. No one will do that for us; scientists have the responsibility to do it themselves. In the future, as in the past, sustained support for scientific work will depend on public understanding.

—*Maxine Singer*

Losses, Gains, Honors. . .

Trustee emeritus Garrison Norton served as trustee from 1960 until 1974 (chairman, 1971). He died on September 9, 1995 at the age of 94. Norton's government service included appointments as assistant secretary of state, assistant secretary of the Air Force for Research and Development, and assistant secretary of the Navy for Air. He received the Navy's Distinguished Public Service Award. In his later years, Norton was president of the Institute for Defense Analyses.

C. Stacy French, who served as director of the Department of Plant Biology for 26 years (1947–1973), died on October 13 at the age of 88. French earned his B.S. and Ph.D. degrees from Harvard University and was research fellow at Caltech and the Kaiser Wilhelm Institute, Berlin. He taught at Harvard (1936–1938), the University of Chicago (1938–1941), and the University of Minnesota (1941–1947). French's research interests focused on the nature and function of photosynthetic pigments and the development of specialized instruments for their study. One of those instruments—the French Press, used to break cells


C. Stacy French

apart—is still in use today.

Olin C. Wilson, a staff member at the Observatories, 1936–1974, died on July 13, 1994, at the age of 85. Wilson first served at the Mount Wilson Observatory as a research assistant in 1931. Wilson earned his Ph.D. from Caltech, the first astronomer to do so. Wilson was a pioneer in stellar spectroscopy. In the 1950s, he showed that the strengths of the H and K emissions were correlated with the ages of main-sequence star groups. Later, he discovered solar-like activity cycles in 91 Sun-like stars. This work established a foundation for the emerging field of solar-stellar astronomy. Wilson received the 1984 Catherine Wolfe Bruce Medal of the Astronomical Society of the Pacific.

Olin C. Wilson

Thomas C. Hoering, an organic geochemist with the Geophysical Laboratory since 1959, died on July 22, 1995, at the age of 70. He earned his Ph.D. from Washington University (St. Louis), and then taught at the University of Arkansas. He developed pioneering techniques for studying fossil molecules in rocks and petroleum, including, with Philip Abelson in 1961, techniques for studying the movement of carbon isotopes during biological processes. This work led to Hoering's discovery of ancient organic molecules in Precambrian rocks. Hoering was past president, Geochemical Society, and he received the Society's 1987 Alfred Treibs Medal. In May 1995, he was honored by a three-day "Hoeringfest," attended by 100 researchers from around the world.

Thomas Hoering

David D. Keck, staff member at the Department of Plant Biology (1934–1950), died on March 10, 1995. With Jens Clausen and William Hiesey, Keck performed critical experiments confirming the workings of evolution in nature.

Richard Hewitt worked at the Institution's P Street headquarters, 1949–1982. He assisted in the research of several presidents and later served as administrative officer for services. He died on November 12, 1994.

William Dove, DTM office manager and longtime employee (1934–1978), died on March 27, 1995.

Sylvia Burd, a senior research assistant at the Mount Wilson Observatory (1941–1972), died on September 21, 1995.

Delores Sahlin, Observatories' receptionist (1975–1989), died June 22, 1995.

Bula Nation, Mount Wilson head stewardess (1953–1967), died January 18, 1995.

Kenneth Langone stepped down from the Board of Trustees in November 1994 after a year of service.

David Fork, staff member at the Department of Plant Biology whose laboratory has been a major focus for international collaboration over the years, retired in June 1995 after 34 years of service. Fork received his A.B. and Ph.D. from the University of California, Berkeley. In his early years, Fork worked with C. Stacy French using spectroscopic techniques to define the light reactions of photosynthesis. Recently, Fork's experiments have provided renewed support for energy conservation by a cyclic electron transport pathway, and, in collaboration with Arthur Grossman's group, demonstrated the role of the enzyme superoxide dismutase in preventing damage to photosynthetic membranes in the presence of oxygen.

Glenn Poe, DTM electronics research specialist, retired in October 1994 after 35 years. He participated in field operations all over the world and built much of the equipment used by DTM seismologists.

Nina Fedoroff, a staff member at the Department of Embryology since 1979, resigned in July 1995 to become Willaman Professor of Life Science at Pennsylvania State University and director of the University's Biotechnology Institute.

Gains

Four individuals have been elected to the Board of Trustees of the Carnegie Institution: John F. Crawford, Frank Press, William Rutter, and Michael Gellert.

John Crawford is an attorney in the Paris office of Jones, Day, Reavis & Pogue. He holds a B.A. from Haverford College, an M.A. from the Fletcher School of Law and Diplomacy at Tufts and Harvard Universities, and a J.D. (1984) from Columbia Law School. Crawford is vice-chairman of the Board of the European Council of American Chambers of Commerce, a founding treasurer and director of the French International Arbitration Institute, and a member of the Council on Foreign Relations, New York. He is also a member of the French Legion of Honor.

Frank Press was president of the National Academy of Sciences, 1981–1993, and is now the Cecil and Ida Green Senior Fellow at the Carnegie Institution's Geophysical Laboratory and DTM. He received his M.A. and Ph.D. (geophysics) from Columbia University. From 1977 until 1980 he served as science advisor to President Carter and director of the Office of Science and Technology Policy. He is on the board of the Sloan Foundation and he is a Life Member of the Corporation of MIT.

William Rutter is co-founder and chairman of Chiron Corporation, California. He is also professor emeritus at the University of California, San Francisco, where he served as Herzstein professor in the Department of Biochemistry and Genetics. Rutter received his B.A. from Harvard, his M.S. from the University of Utah, and his Ph.D. from

the University of Illinois. Rutter's primary research interest is in the mechanism of gene expression and the development of human vaccines. He is a member of the Harvard Board of Overseers and the National Academy of Sciences.

Michael Gellert, elected to the Board in December 1995, is a partner in the private investment company Windcrest Partners, in New York City. He received his A.B. from Harvard University and the M.B.A. from the Wharton School of Finance and Commerce. He joined Burnham Lambert's predecessor firm in 1958. In 1967 he created Windcrest Partners.

Augustus A. Oemler, Jr., will become director of the Carnegie Observatories on February 1, 1996. In this capacity he will hold the Crawford Greenewalt Chair for the Director of the Observatories. Oemler currently is professor (and former chairman) of the Yale University Department of Astronomy. He holds the A.B. (1969) from Princeton and the M.S. and Ph.D. (1974) from Caltech. He served as postdoctoral associate at Kitt Peak, 1974–1975, and joined Yale as J. W. Gibbs instructor, 1975–1977, also holding an Alfred P. Sloan Foundation fellowship there (1978–1980). Oemler's primary research interests are the evolution of galaxies and the large-scale structure of the universe. He has collaborated often with the Carnegie astronomers in Pasadena.

Organic geochemist George D. Cody joined the Geophysical Laboratory as staff member in September 1995 after serving as postdoctoral associate and Enrico Fermi Fellow at the Argonne National Laboratory (1992–1995). He earned his Ph.D. in geosciences in 1992 at Penn State, where his research focused on the chemical and physical characterization of the macromolecular structure of kerogen.

Chen-Ming Fan joined the Department of Embryology as staff member in November 1995. He received his B.S. from the National Taiwan University and the Ph.D. (1991) from Harvard University. At Harvard he studied interferon gene regulation. Currently his research focuses on vertebrate development, specifically on the signals that cause muscle, skin, and bones to develop from a common origin.

Honors

DTM's Vera Rubin and the Observatories' Allan Sandage were elected to the American Philosophical Society in April 1995. Rubin was appointed by President Clinton to a committee to select presidential Medal of Science awardees. She delivered the Henry Norris Russell Lecture at the January 1995 American Astronomical Society meeting. It is the Society's highest award. She delivered the Jansky Lecture at the National Radio Astronomy Laboratory at Charlottesville, Virginia, and at Socorro, New Mexico, in November 1994, the Oort Lecture in April 1995 at Leiden University, where she

Frank Press received a 1994 National Medal of Science.

was the Oort Visiting Professor, and the Lindsay Lecture at the NASA Goddard Space Flight Center in June 1995.

DTM director Sean Solomon was elected a fellow of the American Academy of Arts and Sciences. He delivered the W. S. Jardetzky Lecture at the Lamont-Doherty Earth Observatory in November 1994.

H. K. Mao and Russell Hemley of the Geophysical Laboratory were elected fellows of the American Physical Society. Mao was also elected a member of the Academia Sinica, the Taiwanese equivalent to the National Academy of Sciences.

Plant Biology's Olle Björkman was elected corresponding member and Honorary Life Member of the Australian Society of Plant Physiologists.

Plant Biology's Winslow Briggs was the 1995 Sterling B. Hendricks Memorial Lecturer on August 23, awarded in recognition of his contributions to the chemical science of agriculture.

The Geophysical Laboratory's Ronald Cohen received the 1994 Mineralogical Society of America Award for advancing first-principles theoretical studies of minerals. He also received the Doornbos Memorial Prize at the International Association of Seismology and Physics of the Earth's Interior Symposium 1994.

Embryology's Marnie Halpern was named a 1995 Pew Scholar of the Pew Scholars Program in Biomedical Sciences.

Robert Hazen of the Geophysical Laboratory was elected a fellow of the American Association for the Advancement of Science.

Joseph Berry of the Department of Plant Biology gave the J. B. Wood Memorial Lecture at the annual meeting of the Australian Society of Plant Physiologists in September 1995.

Geophysical Laboratory's F. R. Boyd was the Crosby Distinguished Lecturer at the Department of Earth, Atmospheric, and Planetary Sciences at MIT in October 1994.

In 1995, Geophysical Laboratory's Hatten S. Yoder, Jr., became president of the History of Earth Sciences Society, and received an honorary doctorate of engineering from the Colorado School of Mines.

Former DTM fellows Paul Rydelek (Memphis State University) and Fred Pollitz (University of Cambridge) received an outstanding research paper award from Sigma Xi for "Fossil Strain from the

1811–1812 New Madrid Earthquake," in *Geophysical Research Letters*.

Former Embryology staff associate David Schwartz (New York University) received an award from the American Society for Biochemistry and Molecular Biology for his work in developing pulsed field gel electrophoresis and optical mapping.

Shigeji Suyehiro, former DTM senior fellow and research associate, was elected as only the fourteenth honorary member of the Seismological Society of Japan in March 1995.

Tokindo S. Okada, a former fellow at the Department of Embryology and now director of Biohistory Research Hall, Osaka, received a high honor, the prize "A Person with Cultural Merit," bestowed in November 1995 at the Imperial Palace, Tokyo.

Mizuho Ishida, a former DTM fellow (1982–1983), was elected president of the Seismological Society of Japan.

Embryology business manager Susan Satchell was inducted into Alpha Sigma Lambda.

Geophysical Laboratory interns Aaron Andalman and Marc Hudacsko (Montgomery Blair High School, Maryland) received one of four First Awards for their work on bonding and electron density in crystals in the Team Competition at the 46th Science and Engineering Fair, held by Science Service at Hamilton, Ontario, in May 1995.

Carnegie trustee Philip Abelson received an honorary doctorate of science from Oregon State University in June 1995.

Trustee William T. Coleman, Jr., received a Presidential Medal of Freedom from President Clinton on September 28, 1995.

William Golden received the American Philosophical Society's Benjamin Franklin Award for Distinguished Public Service.

A lecture series honoring Edna and Caryl Haskins was inaugurated in October 1995 at the Rand Corporation in Santa Monica, California.

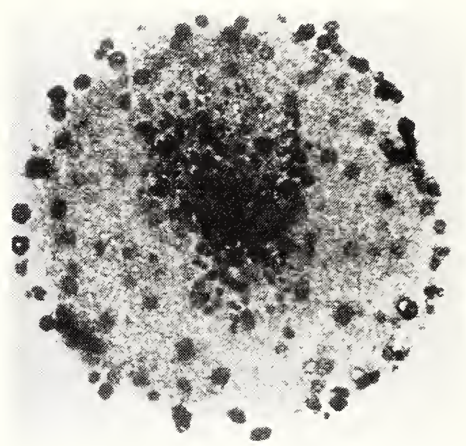
William Hewlett was co-recipient (with David Packard) of the Lemelson-MIT Lifetime Achievement Award in March 1995.

Frank Press received the National Medal of Science on December 19, 1994. He was awarded the first Distinguished Scholar Award by the Columbia University chapter of the Sigma Xi society in April 1995.

Charles Townes was made an honorary fellow of the Rozhdestvensky Optical Society of Russia in June 1995. He was awarded the ADION Medal from the Observatory of Nice, France.

Carnegie president Maxine Singer was selected as one of 50 "Great Americans" by Marquis Who's Who, the publisher of *Who's Who in America*. An exhibit and reception was held October 16, 1995, at the Library of Congress. She was chosen as the 1995 Public Service Awardee of the National Institutes of Health Alumni Association. On November 13, 1995, Singer received a Doctor of Philosophy Honoris Causa from the Weizmann Institute of Science, Israel.

DEPARTMENT OF EMBRYOLOGY



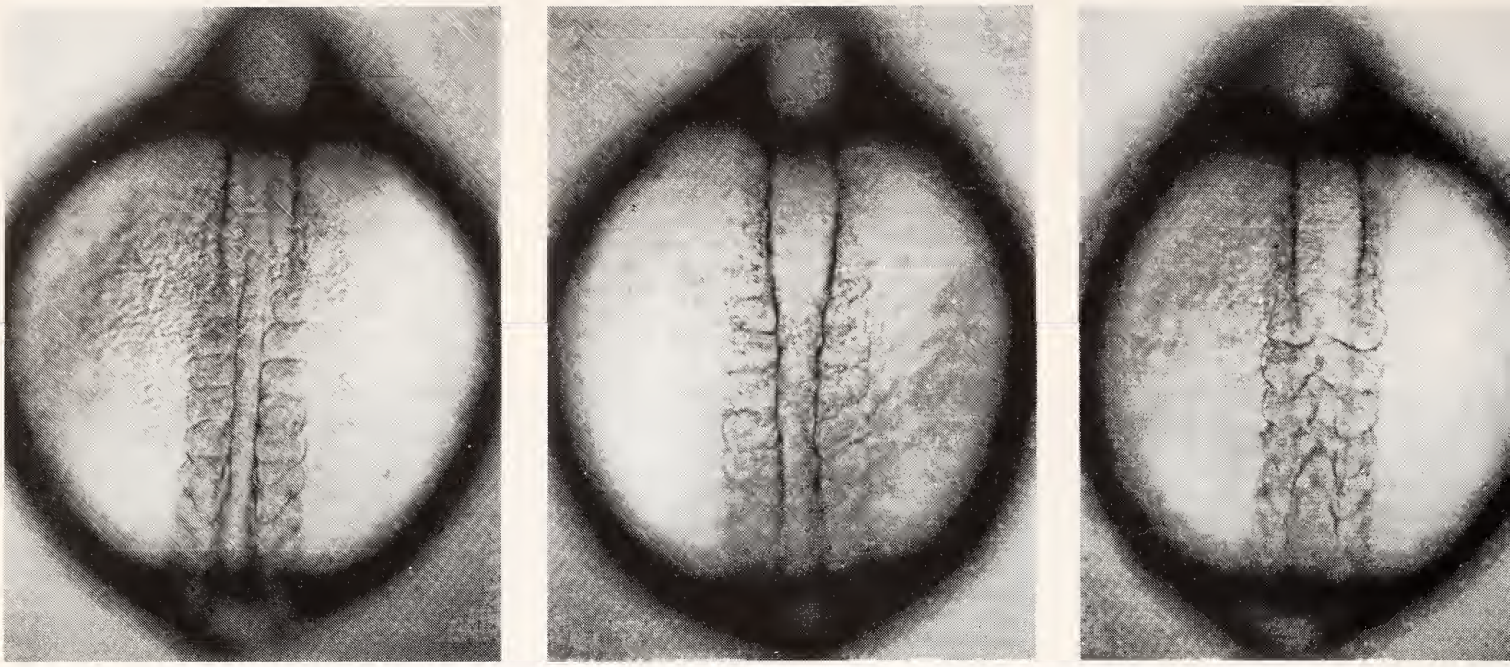
Xenopus oocyte

Members of the Department of Embryology, summer 1995. First row (left to right): Liz Mendez, Kris Belschner, Joohong Ahnn, Allison Pinder, Jessica Blumstein, Ben Remo, Lynne Schneider, James Thomas, Brian Calvi, Earl Potts, Ron Millar. Second row: Jennifer Abbott, Sheri Rakvin, Mei Hsu, Stacey Hachenberg, Irene Orlov, Pat Cammon, Tammy Wu, Michela Denti, Dianne Stern, Linda Keyes, Mary Montgomery, Geraldine Seydoux, Orna Cohen-Fix. Third row: Allan Spradling, Bill Kelly, Jennifer Kalish, Doug Koshland, Rachael Baylin, Shannon Fisher, Chris Murphy, Marnie Halpern, Dianne Stewart, Kathleen Wilsbach, Si-qun Xu. Fourth row: Steve Farber, Paul Megee, Joe Gall, Mike Sepanski, Deborah Berry, Eileen Hogan, Sue Dymecki, Zheng-an Wu, Mary Lilly, Ping Zhang, Akira Kanamori, Nick Marsh-Armstrong, Brian Harfe. Fifth row: Sasha Tsvetkov, Rob Schwartzman, Donna Bauer, Pernille Rørth, Joe Vokroy, John Margolis, Horacio Frydman, Jeff Kingsbury, Bill Kupiec, Steve Kostas, Haochu Huang.

Director's Introduction

Science is a peculiar sort of organism. On rare occasions it can develop in isolation and even blossom in the face of indifference and neglect. But to consistently nurture scientific advances an institution must provide two crucial prerequisites. Outstanding individuals need be identified, recruited, and given the resources they need to formulate and test new ideas. Second, a special atmosphere must be maintained, personally supportive but intellectually critical, to carry novel approaches through their slow-growing early stages and retard the weedy proliferation of merely standard work. During the last seventeen years here, Don Brown has assembled a remarkable group of such individuals, cultivated an exceptionally invigorating atmosphere, and reaped many important advances in our understanding of embryonic development. Although adjustments will be necessary in the coming period where developmental biology will increasingly dominate center stage, his basic strategy will surely continue to serve us well.

The Department of Embryology's research style derives from the ideals of the Carnegie Institution and transcends any particular individual. Indeed, one of the Department's strengths has been its ability to maintain its identity amid healthy turnover among our faculty. This year we were saddened by the departure of two staff members, who greatly contributed to our intellectual life during the last two decades. Dick Pagano developed fundamental methods to track the movement of specific lipid molecules through the cell. During the course of this work, the importance of lipids for embryonic development was increasingly realized as specific lipids were shown to mediate intercellular signals in diverse contexts. Pagano is now Career Scientist and Professor of Biochemistry and Molecular Biology at the



Dorsal views of live wild-type and mutant zebrafish embryos at the ten-somite stage (14 hours post-fertilization). The wild-type embryo (left) has a notochord in the midline, extending anteriorly beneath the hindbrain. The "no tail" mutant (center) has no notochord, and its segmented somites are bilaterally paired on either side of the spinal cord, as in wild-type. In contrast, the "floating head" mutant (right) also lacks a notochord but develops fused somite pairs in the trunk midline beneath the spinal cord. Recent studies by staff member Marnie Halpern indicate that while axial mesoderm is initially present in floating head mutants, it becomes somitic muscle instead of notochord.

Mayo Clinic and Foundation. Nina Fedoroff likewise epitomized many of our research ideals. Shortly after joining our staff she switched fields to study the molecular biology of maize transposable elements, then an uncharted area. Discoveries originating in Fedoroff's lab illuminated the structure and regulation of McClintock's elements, and contributed immensely to our understanding of their role in the host plant. Fedoroff now directs the Biotechnology Institute at Penn State University. Meanwhile Nipam Patel, as staff associate here since 1991, helped integrate our understanding of embryonic development and organismal evolution, one of biology's oldest quests. He has now joined the faculty of the Organismal Biology and Anatomy Department at the University of Chicago, where he is also an Assistant Investigator of the Howard Hughes Medical Institute.

The arrival last fall of Marnie Halpern as a new staff member bolsters the Department's long-standing interest in vertebrate development. The great value of studying embryos that can be manipulated genetically has been described in previous Year Books. Halpern works with zebrafish, a vertebrate in which mutations can be recovered that perturb myriad aspects of patterning and tissue formation. She is particularly interested in the signaling processes that establish and pattern the brain and spinal cord. Halpern has already set up a large facility where numerous zebrafish strains are propagated, and she and the postdoctoral and predoctoral fellows who share her lab have begun to generate and analyze new mutations.

One of the most pleasing aspects of the molecular biology revolution has been the way it has brought previously disparate fields

together. Integration has come horizontally, as common processes are identified that control the development of, for example, worms, flies and humans. Even more surprising has been the degree to which biology is becoming vertically integrated across lines of increasing complexity. Thus, we now recognize that the molecular processes that go on within individual yeast cells or the isolated cells of vertebrates, the province of cell biology, are closely related to the mechanisms controlling how groups of cells interact in an embryo, the traditional realm of developmental biology.

These themes of intellectual unification are highlighted in the topical essays here presented. Joe Gall describes the remarkable discovery that cells contain an important organelle in their nuclei, the coiled body, which until recently seemed a mere curiosity. Coiled bodies mediate the movement of components that are crucial for the proper production of gene transcripts, and are found throughout the animal kingdom. Meanwhile, studies from Allan Spradling's group are beginning to reveal how two fundamental cellular constituents, proteins that control cell growth ("the cell cycle") and cell shape ("the cytoskeleton"), regulate the earliest steps in egg production in the fruit fly.

News of the Department

In June 1995 renovations and new construction were completed, significantly augumenting the Department's research facilities. New laboratories were constructed for two staff associates, and facilities were greatly improved for research utilizing mice and other mammals. The new area is located on the second floor and will be known as the W. M. Keck Foundation Laboratory for Vertebrate Development. We are extremely grateful to the W. M. Keck Foundation, which provided major support for the project. Crucial contributions were also received from the Howard Hughes Medical Institute and from Carnegie trustee Robert Goelet, trustee Gerald Laubach, and Donald Pels. During the opening ceremony on June 2, staff associate Susan Dymecki, who has a new laboratory in the facility, reviewed the long history of mouse genetic research at Carnegie.

Allan Spradling cut the ribbon officially opening the W. M. Keck Foundation Laboratory for Vertebrate Development on June 2, 1995. Standing behind him is postdoctoral fellow Lynne Schneider.

Our seminar program was highlighted by the Eighteenth Annual Carnegie Minisymposium, entitled "Induction and

Patterning of the Vertebrate Nervous System." Chris Kintner, Ali Hemmati-Brivanlou, Igor Dawid, Siew-Lan Ang, Wolfgang Driever, and Andrew Lumsden presented one-hour talks.

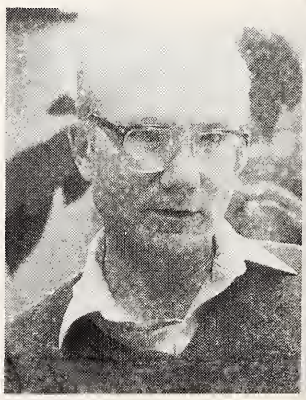
Crucial support for research in the Department comes from sources outside the Institution. I and various members of my lab are employees of the Howard Hughes Medical Institute. We are grateful recipients of individual grants from the National Institutes of Health, the John Merck Fund, the Arnold and Mabel Beckman Foundation, the McKnight Endowment Fund for Neuroscience, the G. Harold & Leila Y. Mathers Charitable Foundation, the American Cancer Society, the Jane Coffin Childs Memorial Fund, the Helen Hay Whitney Foundation, the Damon Runyon–Walter Winchell Cancer Fund, the Rita Allen Foundation, the Human Frontier Science Program, and the Stetler Research Fund for Women Physicians. A grant to purchase small instruments and a Biomedical Research Support Grant to the Department from the National Institutes of Health are gratefully acknowledged. We remain indebted to the Lucille P. Markey Charitable Trust for its support.

—Allan C. Spradling

The Coiled Body—a "New" Cell Organelle

by Joseph G. Gall

Most cell organelles were first described at the turn of the century, when improvements in microscopes and microscopical techniques made it possible to examine cells and tissues at high magnification. Thus the classic accounts of chromosomes, nucleoli, mitochondria, chloroplasts, Golgi bodies, nuclear and cell membranes, cilia, centrioles, and the spindle date from the period between 1880 and 1910. Since then, the hard work for cell biologists has been to find out what these organelles do, and how their structure and function are regulated at the molecular and genetic levels. No one expects a new organelle to turn up nowadays, so the title of this essay needs some explanation and defense.



Joseph Gall

The coiled body was, in fact, seen in the classic period, by no less a figure than the Spanish neuroanatomist and Nobel laureate Ramon y Cajal. Cajal found one or two small, densely stained "dots" inside nuclei of vertebrate nerve cells. These dots were sometimes attached to the more prominent

nucleolus, and for this reason Cajal named them "accessory bodies." The accessory bodies were soon forgotten, except for an occasional reference in the specialized literature of nerve cells. In this respect Cajal was less fortunate than the man with whom he shared the Nobel Prize in 1906, Camillo Golgi. Golgi also discovered a new organelle in nerve cells—in the cytoplasm instead of the nucleus—but the Golgi body, as it came to be called, attracted immediate attention and remained the focus of numerous later studies.

Coiled bodies were rediscovered in 1969 by the French cytologist W. Bernhard, who was studying thin sections of liver nuclei by electron microscopy. Bernhard saw not only the obvious nucleoli but also several smaller structures in the nuclei, one of which (with a bit of imagination) looked like a coiled thread embedded in a more homogeneous matrix. Bernhard's "coiled body" turned up in a variety of cells, including neurons, where it was shown to be the same as Cajal's accessory body.

Still, these structures remained little more than a curiosity for devoted electron microscopists, until a breakthrough occurred in 1991. In that year Eng Tan and his collaborators at the Scripps Research Institute discovered that sera from some patients with autoimmune disease contained antibodies that bound to coiled bodies. The bound antibodies were labeled with a fluorescent probe that gave brilliant immunofluorescent staining of the coiled bodies. Shortly thereafter the Scripps group isolated the gene encoding the protein thus detected by the sera. They named this protein coilin. The original autoimmune sera and additional antibodies produced by the Scripps group at long last provided a simple and highly specific test for identifying coiled bodies in a variety of cell types.

It was quickly discovered that coiled bodies had an interesting and unusual composition. In addition to coilin, they contained several small nuclear ribonucleoproteins (snRNPs, pronounced "snurps"), molecules of extraordinary interest because of their involvement in RNA processing. Specifically, coiled bodies were shown to contain five snRNPs necessary for the conversion of pre-messenger RNA (pre-mRNA) into the mature mRNA that is exported to the cytoplasm.

At that time, our group here at the Carnegie Institution was actively studying snRNPs in the giant nucleus of frog and salamander oocytes, so the work on coiled bodies immediately attracted our attention. Gradually it became clear that the oocyte nucleus also contained coiled bodies. In fact, we and others interested in oocytes had been studying them off and on for over forty years, but under still another name—the sphere, or sphere organelle.

Let me digress briefly to describe our main experimental organism, the African clawed toad, *Xenopus laevis*. Like other amphibians, *Xenopus* lays several thousand eggs that develop rapidly and synchronously

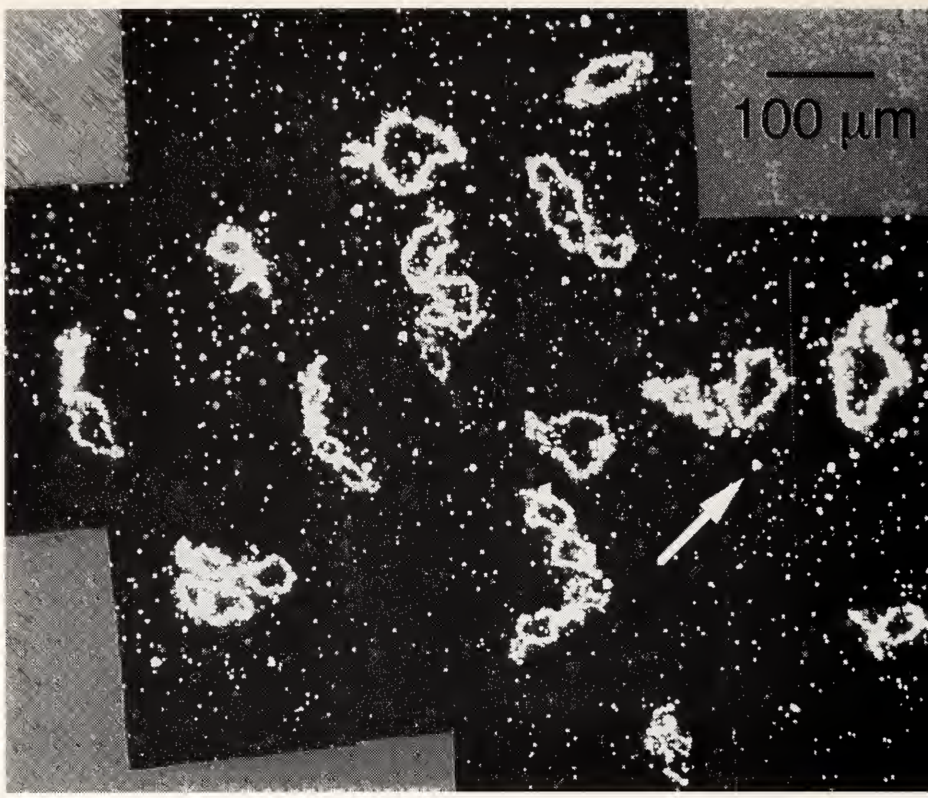


Fig. 1. Low-magnification view of the contents from a single *Xenopus* GV after spreading on a microscope slide; stained with an antibody against the Sm group of snRNP proteins. The eighteen chromosomes are the most prominent feature. The numerous bright granules are primarily snurposomes, among which are interspersed a smaller number of spheres (coiled bodies) (arrow). The nucleoli are not stained by this antibody, and hence are not visible.

into the familiar swimming embryos called tadpoles. Thus *Xenopus* has been useful for embryologists interested in the earliest stages of vertebrate development. The tadpole's remarkable metamorphosis into an adult frog also provides many investigators, including Don Brown and his colleagues here at Carnegie, an accessible system for studying hormone-induced changes in gene expression. Our group studies the oocyte—the egg before it is laid, while it is still inside the ovary. At this time a *Xenopus* oocyte is a single giant cell over 1 mm in diameter. What makes the oocyte so valuable is that it contains a proportionally giant nucleus, about 0.5 mm in diameter, large enough to be seen with the naked eye. The oocyte nucleus was first detected as a tiny fluid-filled vesicle in the hen's egg in 1825, long before it was known to be a nucleus, indeed before the egg itself was recognized as a single cell. It was designated the germinal vesicle, or GV, a name that has stuck ever since.

The GV can be isolated by hand with jeweler's forceps and its contents spread on a glass slide for observation under the microscope (Fig. 1). It contains the giant lampbrush chromosomes, whose name also dates from the 19th century, when investigators likened these fuzzy structures to the brushes used for cleaning lamp chimneys. We now know that the projections responsible for this appearance are loops of DNA on which intense RNA transcription is taking place: in short, the loops are active genes. Besides the chromosomes, a *Xenopus* GV contains three major morphological components (Fig. 2A): nucleoli, snurposomes, and spheres (coiled bodies). The nucleoli are the largest of these and have been the subject of intense study by many investigators over the years, again including Don Brown's group here and mine while I was still at Yale. Each of the thousand or so nucleoli in the mature GV contains a circular DNA molecule that contains from one to many copies of the genes coding for ribosomal RNA. In an earlier stage of oogenesis these genes had somehow gotten out of the

chromosome that usually carries them, and replicated as independent, plasmid-like molecules. In the later stages of oocyte growth, the nucleoli synthesize ribosomal RNA, which is exported to the cytoplasm to provide a large store of ribosomes, protein manufacturers for the developing embryo.

Spheres were first recognized as a distinct GV component in work I did as a graduate student in the early 1950s. As can be seen in Figure 2, they are about the same size as the nucleoli, are remarkably spherical in shape, and often have smaller bumps on their surface. Most of the 50–100 spheres in a GV are "free" in the nucleoplasm, but a few are attached at specific loci on the chromosomes (at two loci in the newt *Notophthalmus*, where they were first seen, and four in *Xenopus*). Quite a lot of morphological information was gathered over the years about spheres, but they remained pretty much unknown outside the community of GV aficionados. One important fact came to light accidentally when we were studying histone mRNA in the late 1970s; namely, the histone genes (whose proteins serve as structural elements of chromosomes) are located precisely at the sites where spheres are attached to the chromosomes. Thus, the existence of free and attached spheres and their association with histone genes were the main facts known about spheres until about six years ago, when we decided to study snRNPs in the GV.

It is well known that all RNAs transcribed in the nucleus are extensively modified before they are exported to the cytoplasm. In the

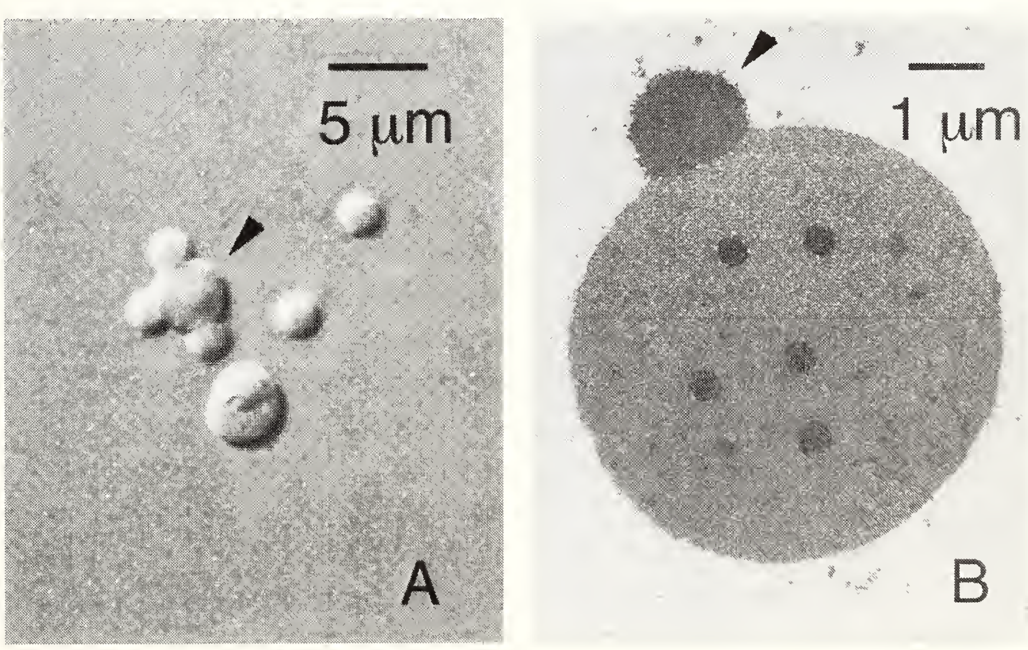


Fig. 2. (A) High-magnification view of a single sphere (coiled body) (arrowhead); three snurposomes are attached to its surface. A nucleolus is seen below the sphere, and two free snurposomes are to its right. This field is a small area from a spread preparation like that in Fig. 1. (B) Electron micrograph of a thin section through a sphere (coiled body). The arrowhead points to a snurposome on its surface. Note the perfectly circular outline of this organelle, which originally suggested the name sphere.

case of most mRNAs, the modification involves cutting out large chunks (introns) from the initial transcripts and splicing the remaining pieces together in a precise fashion. Similarly, the three ribosomal RNAs (the so-called 18S, 28S, and 5.8S molecules) are transcribed as a single unit which is then progressively cut and trimmed to give the final products. The splicing and processing reactions take place in the nucleus, and they require a whole battery of snRNPs. The snRNPs are a special type of enzyme, each of which consists of a small RNA molecule and several associated proteins. Currently, more than twenty different snRNPs are known, designated U1, U2, U3, etc. because their RNAs are rich in U (uridine). The removal of introns from pre-messenger RNA molecules requires five snRNPs: U1, U2, U4, U5, and U6. The processing of ribosomal RNA is known to require U3, U8, and U22, and there is a strong presumption that several others are involved as well. U7 is rather special, and is a major player in the coiled body story. U7 is required for a trimming reaction that removes the "tail" from the pre-mRNA molecules that code for the five histone proteins.

The first thing we wanted to know about snRNPs in the GV was where they were located. In principle this was an easy task, because we had two kinds of probes that could be used to identify snRNPs in spread preparations of GV contents: radioactive nucleic acid probes that could be hybridized to the snRNAs in situ, and antibodies against proteins associated with the snRNAs. We found that the five snRNPs involved in splicing (U1, U2, U4, U5, and U6) were in two places: on the lampbrush chromosome loops and in thousands of small granules that we named snurposomes, because they contained snurps (Fig. 2A). What we saw in the spheres, however, was puzzling. The "bumps" on the spheres were obviously the same as the much more numerous free snurposomes (Figs. 2A and 2B). However, the main body of the sphere did not hybridize with probes against any of the five splicing snRNAs, even though it did stain intensely with an antibody against a group of common snRNP proteins (the so-called Sm proteins). Furthermore, it stained with an antibody against a part of the snRNA molecule itself called the trimethylguanosine cap. So there seemed to be an unknown snRNP in the spheres.

The unknown snRNP turned out to be U7, shown by postdoctoral fellow Herbert Wu, who used in situ hybridization to demonstrate U7 snRNA in the main body of the sphere. Wu also showed that U7 snRNA injected into the cytoplasm of *Xenopus* eggs is rapidly and specifically localized in the spheres. Because U7 is the snRNP necessary for cutting off the end of the pre-mRNA for histones, the observations suggested strongly that a major function of spheres is to import the U7 snRNP from the cytoplasm to the histone gene loci, where the histone pre-mRNA molecules are made.

Soon we got the first hint that spheres might be related to coiled

bodies. The Scripps group had kindly sent us several antibodies against human coilin protein, and one of these stained spheres in spread GV preparations. To be sure that the staining was due to coilin and not to some other cross-reacting protein, a visiting scientist from Beijing, Zheng'an Wu (no relation to Herbert Wu), studied the synthesis of coilin in the oocyte. With help from senior technician Christine Murphy, he injected synthetic mRNA for human coilin into the cytoplasm and followed the newly synthesized human coilin by immunofluorescent staining. He found that human coilin was imported into the nucleus and localized specifically in the spheres. He also showed that a short region at the amino terminus of coilin was responsible for the localization. At about the same time a former postdoctoral fellow in our lab, Mark Roth, then at the Fred Hutchinson Cancer Research Center, and his student Rabiya Tuma, cloned the gene encoding *Xenopus* coilin and showed that *Xenopus* coilin is found in the spheres. Taken together, the evidence strongly suggested that coiled bodies of somatic nuclei and the spheres of the GV were the same organelle. Curiously, although the evidence was compelling for an involvement of spheres in histone mRNA processing, no such association had been demonstrated for somatic coiled bodies. To our great satisfaction, a recently published paper shows that coiled bodies in human tissue culture cells do, in fact, contain U7 snRNA, and that a fraction of somatic coiled bodies are located adjacent to histone genes.

Coiled bodies are not limited to vertebrate cells, shown by collaborative studies with Sasha Tsvetkov from the Institute of Cytology in St. Petersburg, Russia. Tsvetkov has examined a large spherical organelle in GVs of the cricket and other insects, and shown that it contains coilin and snRNPs. Not surprisingly, this organelle was seen by classical cytologists, in this case going under the German name *Binnenkörper*.

In related work, graduate student Donna Bauer is studying the formation of coiled bodies using an in vitro nuclear assembly system. About ten years ago it was shown that *Xenopus* sperm heads would swell to form typical nuclei if placed in an appropriate extract of *Xenopus* eggs. Although small granules were noticed inside these nuclei by several investigators, it was not realized that these were coiled bodies until Bauer began her studies two years ago. She showed that these coiled bodies contain all of the splicing snRNPs (U1, U2, U4, U5, and U6), as well as the U7 snRNP. Remarkably, they also contain U3 and U8 snRNPs and several proteins usually found in the nucleolus.

The in vitro system provides a unique opportunity to study the formation of coiled bodies after removing or altering components in the egg extract. Bauer has already shown that morphologically typical coiled bodies form in extracts from which coilin was removed by immunoprecipitation. Thus coilin—the protein that is so widely used as

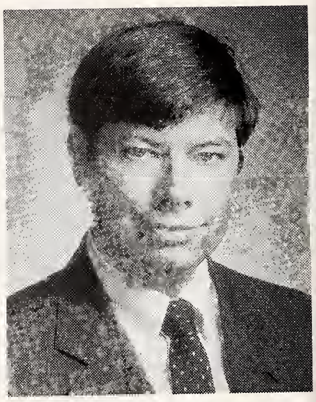
a marker for coiled bodies—is not an essential structural component of coiled bodies, although it may well be necessary for their normal functions.

The coiled body was described many years ago under several different names, yet only recently has it been recognized as a universal nuclear component. Investigators in several laboratories are now studying it intensely, and speculation abounds as to its role in the nucleus. Because it contains such a variety of snRNPs, it must be involved in several aspects of nuclear RNA processing besides histone mRNA processing. This is an exciting time for members of our laboratory and other groups interested in coiled bodies; cell biologists seldom get an opportunity to investigate an important cell organelle about which so little is known.

The Fusome and Early Germ-Cell Development

by Allan C. Spradling

Germ cells are unique among the many types of cells in developing embryos. Only germ cells, after becoming eggs or sperm, will give rise to subsequent generations of the organism. Possibly for this reason, the behavior of germ cells during embryogenesis has long been an important focus of research in developmental biology. Germ cells frequently appear to remain aloof from the frenzied activities of the embryo's non-germ, or somatic, cells, as though their status as progenitors exempted them from average workaday requirements. Even the internal structure of early germ-line cells is distinctive; they lack a specialized shape, and their organelles frequently lie together in large clusters as if in storage, rather than dispersed around the cell in a manner suggesting active function. Our lab group has long been fascinated with these unusual biological properties of germ cells.



Allan Spradling

Research that began in our lab about six years ago recently yielded new insight into one distinctive germ-cell property. Germ cells in many organisms, including both humans and fruit flies, develop as groups of interconnected cells known as cysts, rather than individually. Eggs in *Drosophila* grow as part of sixteen-cell cysts (Fig. 1), and groups of human egg precursors are also interconnected during early developmental stages, although the exact number of cells per cyst may vary. A distinctive process of incomplete cell division is thought to

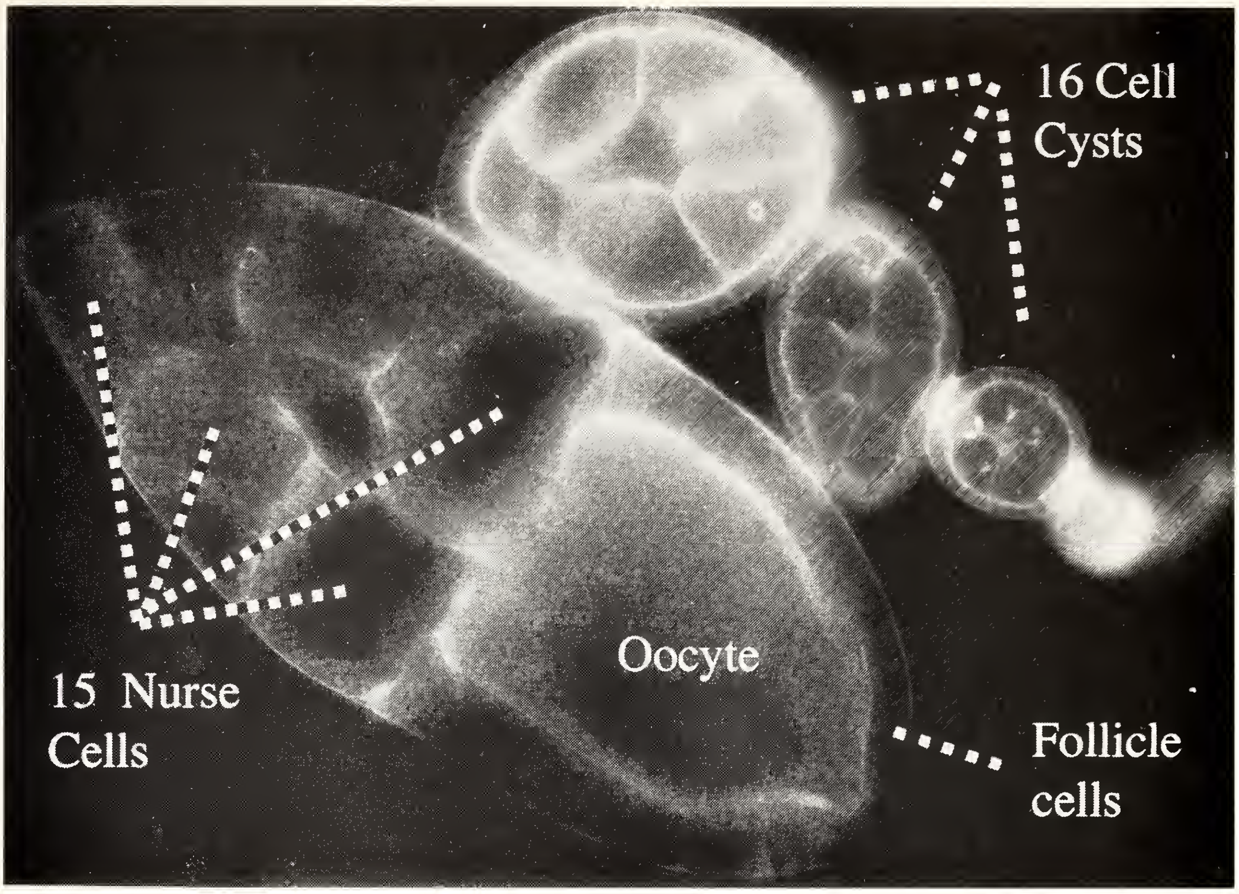


Fig. 1. Developing egg precursors from the *Drosophila* ovary consist of sixteen-cell cysts surrounded by a layer of follicle cells. A string of increasingly larger and more mature egg precursors is shown starting at right. As development progresses the fifteen nurse cells grow to enormous size. The future oocyte expands rapidly and eventually becomes larger than its nurse cells due to the receipt of components synthesized in the nurse cells and transported continuously through the intercellular junctions known as ring canals. This preparation was treated with a specific stain that labels the structural protein actin, a major cellular component located near membranes and in the ring canals. Several of the ring canals are visible as small circular structures. The length of the large cyst at the bottom of the picture is about 0.3 mm.

produce germline cysts in these and many other species.

When a cyst cell divides, the two daughter cells do not completely separate as they would in a normal division. Instead, a small interconnecting channel is maintained, even as the two cells go on to divide further and generate still further connections. These cyst-producing mitotic divisions are unusually rapid and occur in precise synchrony, unlike the divisions of cells in other tissues, which occur at independent times even among neighboring cells. Growth by synchronous doublings explains why the number of cells in a cyst is frequently a power of two; thus, the sixteen cells of the *Drosophila* ovarian cyst arise from four rounds of coordinated division. New cysts arise successively from a common cyst-forming region, to form strings of cysts.

The reasons why germ cells usually develop in cysts are not known with certainty, nor has the importance of synchronous divisions been established. After reaching the sixteen-cell stage, the germ cell undergoes meiosis, a special cell cycle that reduces the number of chromosomes by half and re-assorts genetic variation by recombination. The decrease allows the normal chromosome number to be restored upon fertilization. However, it also means that the individual egg or sperm cell will only contain half its parent's gene

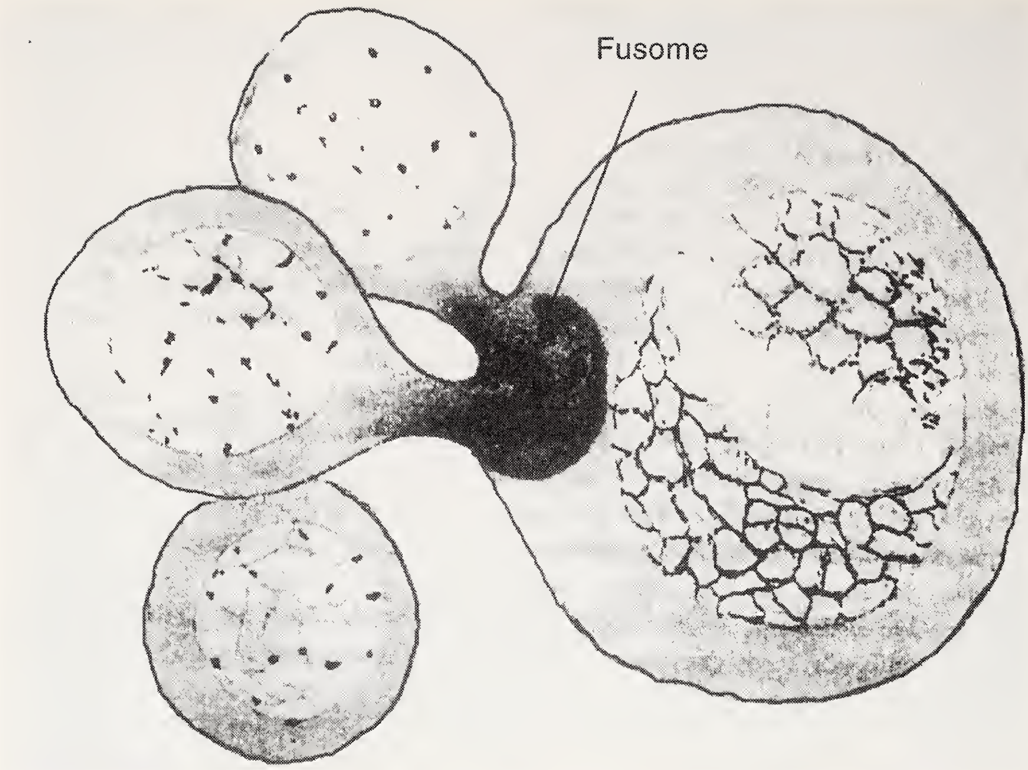


Fig. 2. Cyst formation in the diving beetle ovary is associated with an unusual cytoplasmic structure, the fusome. This drawing was taken from the classic 1901 paper by Giardina. It shows a partially completed ovarian cyst that has undergone the first two synchronous divisions to yield a cyst of four cells, as seen in the light microscope. (The junctions joining three of the cells are visible, while the connection to the third is located below the focal plane shown in this drawing.) The large cell at the right is the cyst progenitor cell, which in this species always becomes the oocyte. The smaller cells will become nurse cells. Material that will form Giardina's ring can be seen in the nucleus (center) of the oocyte, while the dark mass in the oocyte cytoplasm near and within the intercellular junctions is the fusome.

copies. Development within a cyst probably compensates for this by allowing each developing germ cell to share all the parental gene products, regardless of which particular gene copies it inherits. This is particularly important for male germ cells, which develop extensively after the chromosome reductions have taken place. Another cyst function, which can be crucial for female germ-cell development, is to propel rapid egg growth through cell specialization. In *Drosophila*, fifteen of the sixteen cyst cells function as "nurse" cells, which actively synthesize and transport materials into the oocyte for later use during embryonic development (Fig. 1). Having completed their task, the nurse cells are programmed to degenerate just before the oocyte becomes the fully mature egg. Extensive degeneration is also observed among interconnected human female germ cells, although there is presently no evidence that they function as nurse cells.

One clue to understanding how germ-line cysts form first appeared in a classic 1901 paper by the Italian embryologist Giardina (Fig. 2). He studied cyst cell division in the ovaries of a large, European diving beetle found in freshwater ponds. Giardina's paper noted two extraordinary things about these dividing cysts. First, a large circular mass of nuclear material, "Giardina's ring," is retained by the large, cyst progenitor cell rather than passing equally, as normally expected, into its smaller daughters. More than twenty years ago Joe Gall explained the origin of Giardina's ring. It contains multiple copies of

the genes encoding the major RNA components of ribosomes, the cell's machinery for protein synthesis. These extra gene copies are produced by "gene amplification," a process independently discovered earlier by Gall and Donald Brown while studying amphibian eggs. Second, Giardina also observed a dense mass of unusual cytoplasmic material, which following unusual movements ends up adjacent to and within the junctions between the cyst cells (Fig. 2, "fusome"). The significance of the cytoplasmic structure, which became known as the fusome, remained obscure.

Subsequent studies confirmed that a distinctive cytoplasmic aggregate, i.e., the fusome, is associated with the process of cyst formation in a wide variety of insects. Pioneering studies in the 1970s by Robert King of Northwestern University established that cysts developed abnormally and contained abnormal fusomes in *Drosophila* having mutations that cause benign ovarian tumors. In 1975 Robert Telfer of the University of Pennsylvania Medical School summarized the state of knowledge in an influential review. However, it remained impossible to critically test several competing hypotheses: (1) fusomes might play a role in generating intercellular bridges, possibly by simply blocking the normal process that pinches dividing cells in two, since fusomes are present during cyst formation and occupy these interconnections, (2) they might also participate in determining which cells of the cyst become nurse cells and which becomes the oocyte, by controlling the movement of material between cells, and finally (3) fusomes might be important for the unusually rapid, synchronous cell cycles of forming cysts. Perhaps most frustrating of all was the continued failure to identify even a single molecular component of fusomes. As progress stagnated, knowledge that fusomes even existed gradually became limited to only a handful of specialists.

There are many such unsolved problems in cell and developmental biology. Genetically tractable organisms such as *Drosophila* allow one to pursue general experimental approaches that do not depend on understanding the function of a structure such as the fusome or physically isolating its molecular components. In 1989 a graduate student in the lab, Lin Yue, and I reasoned that a greater knowledge of cyst formation would likely come from identifying and cloning genes that disrupted this process specifically. We generated and began to analyze mutations in a gene Yue named *hu-li tai shao* (abbreviated *hts*). Females bearing *hts* mutations are sterile, and their developing cysts contain an average of only four rather than sixteen cells (Fig. 3)—hence the name, which in Chinese means "too little nursing." Yue cloned the gene and showed that it encodes proteins that are closely related to the vertebrate protein adducin. Adducin forms part of the protein superstructure of mammalian cells, the "cytoskeleton." It helps link up another skeletal protein, called spectrin, into a network that lies just

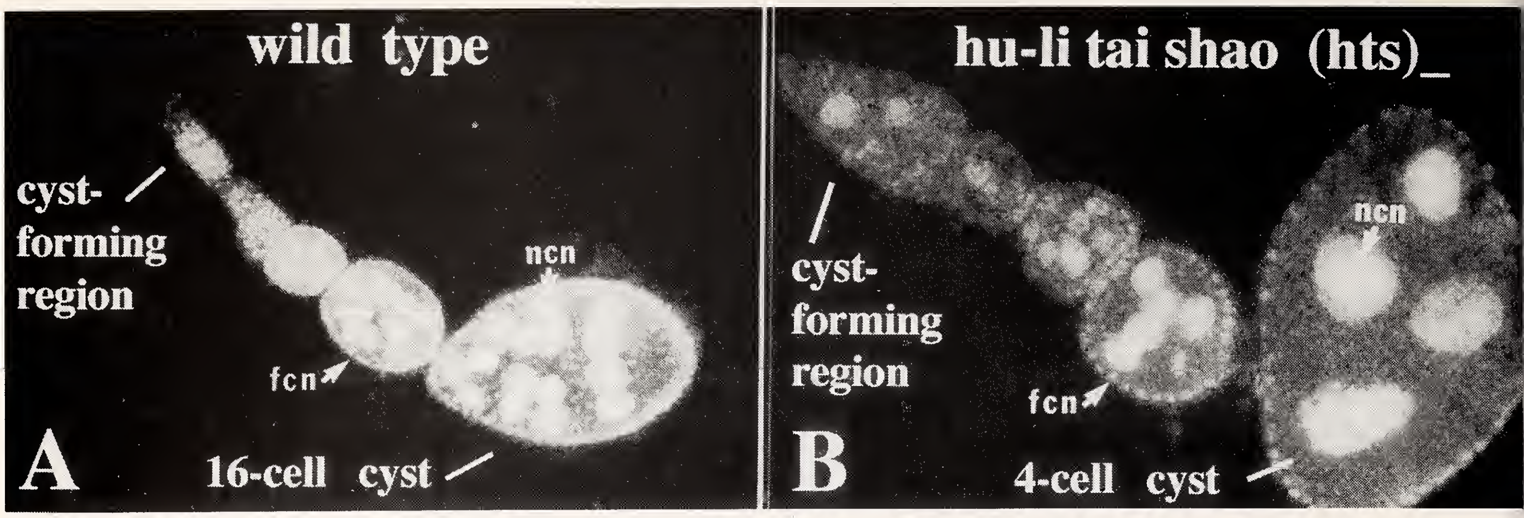


Fig. 3. Egg strings are compared from wild-type females (A), and from females bearing the *hu-li tai shao* (*hts*) mutant (B). The cyst-forming region is indicated near the small end of each string, joined by four developing egg precursors. The preparations were stained to highlight the DNA within the nurse cell nuclei (ncn) of the developing cysts, and their surrounding follicle cells (fcn). The wild-type cysts can be seen to contain fifteen nurse cells (the oocyte nucleus contains too little DNA to be readily observed). In contrast, the cysts from the *hts*-mutant female contain a reduced number of cells; for example, the largest cyst shown contains just four nurse cells.

under the cell membrane, where it provides support much like the poles of a tent. Adducin is found at the joints of the spectrin "poles." We now know that this system for supporting membranes is widespread throughout the animal kingdom. Thus our genetic analysis implicated a well-known group of proteins in the process of cyst formation whose role had been entirely unsuspected.

To learn more about the possible function of the Hts protein, we needed to determine where it was located in dividing cysts. When antibodies were prepared with the assistance of former Carnegie postdoctoral fellow Lynn Cooley and her student Kelly Cant, a gratifying result was observed by Yue and postdoctoral fellow Haifan Lin (Fig. 4). Although the Hts protein recognized by the antibody was located under cell membranes in most cell types, in developing ovarian cysts it was present only in a large branched structure that connected the individual cells through the ring canals—the fusome! Spectrin antibodies were tested and showed a similar result. Postdoctoral fellow Maggie de Cuevas subsequently localized two other membrane skeleton proteins there as well.

Thus the fusome consists at least in part of proteins that in many cells generate a sub-membranous scaffold. In the *hts*-mutant cysts, the fusome appeared to be completely gone. Most likely, without Hts protein at the sites where joints should form, the spectrin molecules could not be held in place to maintain its structure, causing it to fall apart. Thus a detailed study of cyst formation in *hts* mutants allows us to ask what defects result when cysts try to form without a fusome. Moreover, when we looked at early germ cells prior to cyst formation, we found that spectrin and Hts proteins are aggregated into a spherical structure. We suspect that membrane skeleton proteins also contribute to the unusual way cytoplasmic organelles are organized in early germ cells.

Further studies by Lin, de Cuevas, and postdoctoral fellow Mary

Lilly have begun to reveal a clearer picture of how the fusome contributes to cyst formation. We could rule out the first postulated function, that fusomes blocked cell division to create the intercellular junctions. Apparently normal interconnections were observed between the limited number of cells within *hts*-mutant cysts, at least initially. In contrast, we confirmed that the fusome was probably required for the proper specification of the oocyte and nurse cells. In *hts*-mutant cysts, we found that oocytes rarely form and that the ability to transfer components through the ring canals is severely impaired. Further, the fusome may polarize the cyst cell divisions, thereby ensuring that the initial cell will be the one that receives transported materials from all the others and becomes the oocyte.

However, it remains possible that the defects in oocyte formation result from a second function of Hts proteins. Research in Cooley's lab has shown that an altered form of Hts becomes incorporated into the ring canals several days after they initially form, at the time the fusome is breaking down. This form of Hts appears to be required for actin protein to associate with the ring canals (Fig. 1). Actin-binding may be a feature of Hts that is conserved in evolution, since mammalian adducin binds actin in vitro and in the membrane skeleton. A thick ring of actin and Hts protein is probably necessary for the ring canals to expand and transport efficiently as the nurse cells grow larger.

Surprisingly, the third postulated function, i.e., controlling the rapid and synchronous cyst cell cycles, now appears to be a primary function of the fusome. Work by Lin and de Cuevas has shown that in *hts*-mutant females, the cyst divisions no longer occur synchronously. Also, cyst cells probably cease dividing prematurely, and this may be the reason that the number of cells per completed *hts*-mutant cyst is reduced. Reduced cell division does not correspond to a change in the rate of growth, however, as *hts*-mutant cysts are approximately the same size when they become surrounded by follicle cells as wild-type cysts. As a result some of the cells in the cyst-forming region of *hts* egg strings are larger than in wild type (Fig. 3, compare A and B).

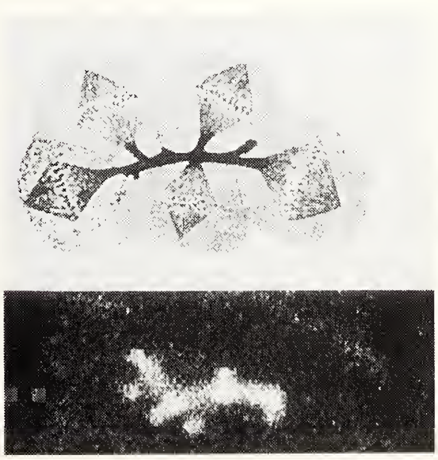


Fig. 4. A *Drosophila* wild-type ovarian cyst. In the drawing at top, the fusome can be seen as a dense, branched structure toward the center joining all the cells of the cyst. In the photograph below, a single, newly completed cyst is magnified to about the same size for comparison. The preparation was stained to reveal the location of the Hts protein. Hts can be seen to lie in a dense, branched structure nearly identical to the fusome in the drawing.

In similar preparations of ovarian cysts taken from *hts* mutants, no fusome staining can be observed. Additional experiments verified that the fusome itself is gone, along with the Hts protein.

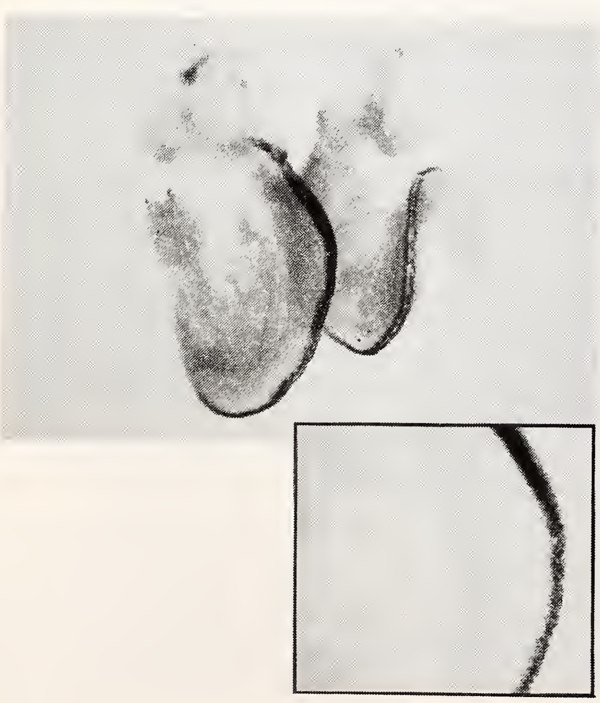
We recently observed that cyclin A, a major cell cycle regulatory protein, becomes transiently associated with the fusome during a limited part of the cyst cell cycles. This association may provide a molecular explanation for how the cyst cell cycles are synchronized. We now suspect that the fusome acts as a scaffold to concentrate and efficiently distribute cell cycle regulators throughout all the cells of the cyst.

Our studies of germ-line cyst formation are far from complete. We still do not understand the importance of synchrony for germ-cell development. However, if cyst cells must share products produced by genes located in different cells, synchrony may be necessary to ensure that the receiving cells are in appropriate developmental states to utilize products at the times they are made and transported. Thus, sharing of gene products may be inextricably linked to a requirement for synchrony. The fact that we can now modify the process of cyst formation genetically with increasing precision and specificity should allow us to test these ideas and learn still more about those unique cells, the germ cells.

Short Reports

Susan Dymecki

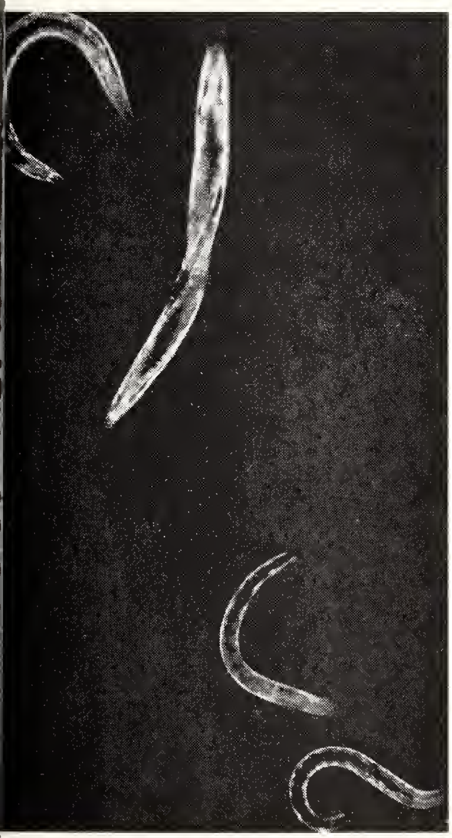
To generate new methods for visualizing and genetically manipulating somatic cell lineages, a recombination-based cell-marking system (using FLP recombinase) is being developed in the mouse. FLP catalyzes recombination between direct repeats of target DNA sequences (FRTs), excising the intervening DNA. Exploiting this property, a binary system has been generated, which consists of "effector" mouse lines expressing FLP in specific progenitor cells and potential "target" mouse lines carrying an FRT-disrupted *lacZ* gene (βGal-). In doubly transgenic (effector/target) embryos, FLP-mediated excision of FRT sequences in the progenitor cells should switch on the lineage tracer βGal in a heritable fashion. I plan to use this cell-marking system to study mechanisms that underlie induction and patterning of this vertebrate nervous system. Towards this goal, transgenic mouse embryos expressing FLP in the dorsal aspect of the developing central nervous system have been generated and are shown here (dark staining reflects FLP mRNA.)



When this frog was a tadpole (left), its tail was amputated and the teratogen, retinoic acid, was placed in its water for three days. Normally, the tadpole would have regenerated its tail, but the retinoic acid inhibits this process. Instead, tail cells are changed to limb cells. Then, when the tadpole metamorphoses to a frog (right), a new set of limbs grow from the end of the tail as the rest of the tail resorbs. Alejandro Sanchez, working in Donald Brown's lab, is identifying the genes that accompany this change.

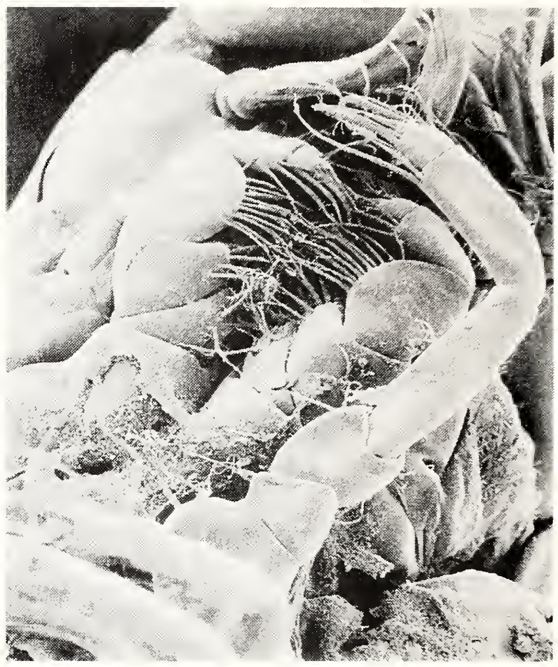
Andrew Fire

The Fire lab uses *Caenorhabditis elegans* (a nematode) as a model organism to study events leading to cellular diversification during embryogenesis. Much of the work in the last several years has focused on describing the genetic pathways controlling muscle-cell development. Recent technology has allowed visualization of muscle-cell lineage in live animals, by "borrowing" a gene segment which is responsible for the green fluorescent appearance of some jellyfish. The nematodes shown in the photo have been engineered to express the jellyfish "Green Fluorescent Protein" using the control elements from a gene (*myo-3*) normally expressed in nematode skeletal muscles. Skeletal muscle fluorescence in these transgenic animals can be used as an indicator of muscle differentiation in a variety of experiments, including genetic screens for mutants affecting muscle patterning.



Nipam H. Patel

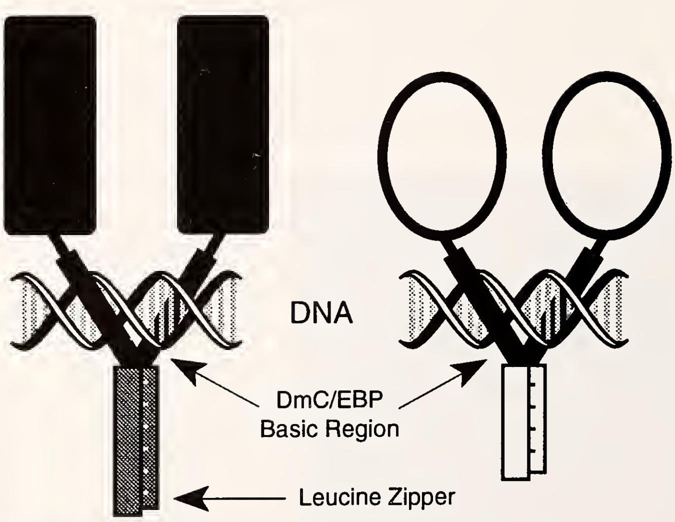
My lab continues to study the evolution of segmentation and neurogenesis. During the last year we have become especially interested in the relationship of appendage patterns in insects and crustaceans. This scanning electron micrograph of a mysid shrimp shows several of the anterior thoracic appendages. Our studies suggest that alterations in the regulation of homeotic genes, a set of master regulatory genes found in all animals, appears to be responsible for the evolution of various appendage morphologies within the crustaceans. In addition, we have found that the two-branched (biramous) pattern of crustacean appendages arises from a split in the dorso-ventral axis of an initially single-branched (uniramous) appendage such as that found in insects. (Only the innermost appendage branches are visible in this micrograph.) These results provide important insights into the molecular genetic mechanisms responsible for the evolution of various animal body forms.



Thyroid hormone is essential for proper development of the brain. This photograph, obtained in the research of Catherine Thompson, depicts the expression pattern of a novel thyroid hormone responsive gene (Srg1) in rat brain. Shown is in situ hybridization of a coronal section of cerebellum; dark areas reflect the presence of RNA from this newly identified gene. Srg1 RNA is not detected in the brains of thyroid hormone deficient animals. Identification and characterization of genes whose expression is thyroid hormone dependent will shed light on the molecular mechanisms underlying developmental processes in the mammalian central nervous system. See *Year Book 92*, pp. 36–41.

Pernille Rørth

DmC/EBP is a basic region/leucine zipper transcription factor which plays an essential role during *Drosophila* embryogenesis. A transgenic rescue assay was used to determine which molecular features of DmC/EBP are necessary and sufficient for its function in vivo. The figure shows a schematic representation of DmC/EBP on the left and one of the chimeric proteins that could substitute for DmC/EBP on the right. Surprisingly, the short, evolutionary conserved basic region was sufficient to specify DmC/EBP activity in vivo. I am now developing a novel type of genetic interaction screen, which will be used to identify other gene products important for DmC/EBP function during development.



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Personnel

Research Staff

Donald D. Brown
Nina V. Fedoroff
Andrew Z. Fire
Joseph G. Gall
Marnie Halpern[1]
Douglas E. Koshland
Richard E. Pagano[2]
Allan C. Spradling, Director

Staff Associates

Susan Dymecki
Nipam Patel[3]
Pernille Rørth
Catherine Thompson

Postdoctoral Fellows and Associates

Joohong Ahnn, Research Associate, NIH Grant (Fire)
Amy Atzel, Fellow of the NIH[4]
Brian Calvi, Fellow, American Cancer Society
Chii-shiarng Chen, CIW[5]
Orna Cohen-Fix, International Human Frontier Science Program Fellow[6]
Maggie de Cuevas, Howard Hughes Research Associate
Steve Farber, Fellow, Markey Charitable Trust[7]
Shannon Fisher, Stetler Research Fund for Women Physicians[8]
David Furlow, Fellow of the NIH
Elena Georgieva, Research Associate, NIH Grant (Fedoroff)[9]
Vincent Guacci, Fellow of the NIH
Kentaro Hanada, International Human Frontier Science Program, NIH Grant (Pagano)[5]
Elizabeth Helmer, Research Associate, Mathers Charitable Foundation (Brown)
Akira Kanamori, Research Associate, Mathers Charitable Foundation (Brown)
William Kelly, Fellow of the NIH
Linda Keyes, Fellow of the NIH

At the dedication of the W. M. Keck Foundation Laboratory for Vertebrate Development on June 2, 1995, Susan Dymecki (left), Catherine Thompson, James Thomas, Stacey Hachenberg, and Meg Bottcher hold a poster depicting varieties of mice. Their CIW mouse shirts were specially made for the occasion.

Mary Lilly, Fellow, American Cancer Society
Haifan Lin, Fellow, Markey Charitable Trust[9]
Jonathan Margolis, Fellow of the NIH
Nick Marsh-Armstrong, Fellow of the Jane Coffin Childs Memorial Fund[6]
Paul Megee, Cancer Research Fund of the Damon Runyon-Walter Winchell Foundation Fellow[10]
Pamela Meluh, Fellow, The Helen Hay Whitney Foundation
Liz Mendez, CIW
Mary Montgomery, Research Associate, NIH Grant (Fire) and Fellow of the NIH
Peter Okkema, Fellow of the NIH, and CIW[11]
Pascal Paul, CIW[5]
Luca Pellegrini, Fellow, Consiglio Nazionale delle Richerche, and CIW[12]
Ramesh Raina, Research Associate, NIH Grant (Fedoroff)[13]
Alejandro Sanchez, Fellow of the NIH
Michael Schläppi, Fellow, Swiss National Science Foundation, and CIW
Lynne Schneider, CIW
Rob Schwartzman, Fellow, American Cancer Society
Geraldine Seydoux, Research Associate, Markey Charitable Trust
David Smith, Research Associate, Markey Charitable Trust
Alexander Strunnikov, Research Associate, NIH Grant (Koshland)
Ryuji Tsugeki, Japan Society for the Promotion of Science Fellow[13]
Zhou Wang, Research Associate, Mathers Charitable Foundation[14]
Kathleen Wilsbach, Research Associate, Markey Charitable Trust[15]
Chung-Hsiun Wu, Fellow of the Jane Coffin Childs Memorial Fund
Ayumu Yamamoto, CIW[16]
Ping Zhang, Howard Hughes Research Associate

Predoctoral Fellows and Associates

Jennifer Abbott, Johns Hopkins University
Jining Bai, Johns Hopkins University
Donna Bauer, Johns Hopkins University
Deborah Berry, Johns Hopkins University
Jessica Blumstein, Johns Hopkins University
Lihsia Chen, Johns Hopkins University
Kim Dej, Johns Hopkins University
Brian Eliceiri, Johns Hopkins University
Horacio Frydman, Johns Hopkins University
Brian Harfe, Johns Hopkins University
Haochu Huang, Johns Hopkins University
Steve Kostas, Johns Hopkins University
Tammy Wu, Johns Hopkins University

Supporting Staff

Betty Addison, Laboratory Helper
Kristin Belschner, Photography Assistant, Technical Assistant
Meg Bottcher, Technician[17]
Ellen Cammon, Laboratory Helper
Patricia Cammon, Laboratory Helper
Duane Campbell, Technician[18]
Adam Elhofy, Technician[19]
Pat Englar, Administrative Assistant
Eugene Gibson, Custodian
Tom Haas, Technician[13]
Stacey Hachenberg, Technician
Eileen Hogan, Senior Technician
Connie Jewell, Photographer
Glenese Johnson, Laboratory Helper
Jeff Kingsbury, Technician
Bill Kupiec, Computer Systems Manager

Ona Martin, Senior Technician
Keith Menchey, Technician[20]
Ronald Millar, Building Engineer
Christine Murphy, Senior Technician
Christine Norman, Howard Hughes Medical Institute Research Secretary
Robinette Oliver, Maintenance
Irene Orlov, Technician
Allison Pinder, Technician
Earl Potts, Custodian
Sheri Rakvin, Administrative Assistant
Benjamin Remo, Technician
Susan Satchell, Business Manager
Michael Sepanski, Electron Microscopy Technician
Loretta Steffy, Bookkeeper/Clerk
Dianne Stern, Technician
Mary Strem, Technician[21]
Dianne Stewart, Senior Technician
James Thomas, Animal Care Technician[22]
Joe Vokroy, Machinst
John Watt, Librarian
Siqun Xu, Technician

Visiting Investigators and Collaborators

Eldon Ball, Australian National University, Australia
Michele Bellini, Lab. de Génétique du Développement, Paris VI University
Michael Edidin, Dept. of Biology, Johns Hopkins University
Zandy Forbes, Dept. of Zoology, Oxford University, Oxford, England
Phil Hieter, Dept. of Molecular Biology and Genetics, Johns Hopkins School of Medicine
Andrew Hoyt, Dept. of Biology, Johns Hopkins University
Ann Hubbard, Dept. of Cell and Anatomy, Johns Hopkins School of Medicine
Michael Krause, National Institutes of Health
Carolyn Machamer, Dept. of Cell and Anatomy, Johns Hopkins School of Medicine
Patrick Masson, Laboratory of Genetics, University of Wisconsin—Madison
Andrei Mirzabekov, Engelhardt Molecular Biology Institute, Moscow
Markus Noll, University of Zürich, Switzerland
Gerald M. Rubin, University of California, Berkeley
Rob Saint, University of Adelaide, Australia
Robert Whittier, Mitsui Plant Biotechnology Research Institute, Tsukuba, Japan
Zheng'an Wu, Institute of Developmental Biology, Academia Sinica, Beijing
Alexander Tsvetkov, Institute of Cytology, USSR Academy of Sciences
Kai Zinn, California Institute of Technology

* * *

[1]From June 1, 1994
[2]To November 1, 1994
[3]To March 1, 1995
[4]To June 11, 1995
[5]To October 31, 1994
[6]From July 1, 1994
[7]From February 1, 1995
[8]From September 1, 1994
[9]To September 30, 1994
[10]From April 1, 1995
[11]To February 24, 1995
[12]To February 28, 1995
[13]To June 30, 1995
[14]To December 31, 1994
[15]From August 1, 1994
[16]To February 14, 1995
[17]From January 9, 1995
[18]From October 1, 1994
[19]From December 26, 1994 to June 30, 1995
[20]To September 1,1994
[21]To August 5, 1994
[22]From July 17, 1994

Department of Plant Biology

Arabidopsis thaliana

Members of the Department of Plant Biology, 1995. First row, left to right: Kirk Apt, Yoko Nishizawa, Catharina Casper-Lindley, Elena Casey, Cesar Bautista, Frank Nicholson, John Davies, and Rakefet Schwarz. Second row: Mannie Liscum, Claire Granger, Paul Oeller, Stewart Gillmor, Jan Jaworski, Chris Somerville, Marsha Pilgrim, and Neil Hoffman. Third row: Geeske Joel, Luc Adam, Carolyn Malmstrom, Anne Ruimy, Devaki Bhaya, Osamu Nishizawa, Greg Colello, Shauna Somerville, Wei Fu, Pierre Broun, Kathi Bump, Wayne Stochaj, Connie Shih, John Quisel, Dennis Wykoff, Peter Kroth, and Sean Cutler. Fourth row: Matthew Thompson, Kris Niyogi, Iain Wilson, Michele Nikoloff, Margaret Olney, Pedro Pulido, Winslow Briggs, and Mary Smith. Top row: Nat Hawker, Deane Falcone, Howard Whitted, Chris Lund, James Randerson, Steven Reiser, Joe Ogas, Devin Parry, Colby Starker, Olle Björkman, Paul Levin (seminar speaker), Glenn Ford, James Zhang, Rudy Warren, Nadia Dolganov, Aida Wells, Arthur Grossman, and Steve Lindley.

Director's Introduction

Recently, an important milestone in biological research was reached. Craig Venter and colleagues at the Institute for Genomic Research, Gaithersburg, Maryland, reported in the journal *Science* the complete nucleotide sequence for the genome of the bacterium *Hemophilus influenzae*. By comparing the *H. influenzae* sequence to the DNA and protein sequences of individual genes and proteins from many other organisms, it was possible to infer the function of about half of the bacterium's genes. Considering the rapid rate at which the functions of new genes are being elucidated, it seems likely that within the foreseeable future we will know the function of all of the genes required to produce a simple living cell.

It is also expected that the complete nucleotide sequence of the genome of the yeast *Saccharomyces cerevisiae* will be completed within the next year by a large team of international collaborators. This will be the first eukaryotic organism for which a complete genomic sequence is available. Preliminary results indicate that the functions of less than a quarter of the yeast genes are known. In order to understand the functions of all the genes in yeast, several research groups have begun to systematically disrupt every gene in the organism, one at a time.

During the next decade, these impressive technical accomplishments will be extended to a number of other organisms, including plants. In particular, work has recently begun on the complete sequencing of the genome of *Arabidopsis thaliana*, a plant widely used in experiments. It is estimated that the *Arabidopsis* genome contains about 20,000 genes within a total sequence of 100 million base pairs—a fifty-fold increase over that of the *H. influenzae* genome. The projected date for completion of the *Arabidopsis* genome sequencing is 2004. Thus, it does not seem too soon to be thinking about the implications.

It will, for example, become increasingly easy to identify a gene corresponding to a particular mutation by genetically mapping the mutation relative to molecular markers derived from the genomic sequence. It is, thus, an opportune time to begin expanding the collection of *Arabidopsis* mutants even though it is not currently feasible to determine the molecular basis of many of the mutations. Furthermore, since many of the potentially most informative mutations are likely to be in indispensable genes that regulate growth and development, methods must be developed to isolate conditional mutants, i.e., where the mutation is expressed only under certain conditions. Virtually no useful mutations of this kind are currently available, and interest in this approach has been minimal because of the current difficulty of isolating the corresponding genes.

Another implication of the genome projects is that it will become increasingly easy to identify the functions of genes and proteins by referring to information about homologous genes in other kinds of organisms. It is already apparent, from the partial sequencing of more than 30,000 plant cDNA clones, that the probable function of many plant genes can be inferred by comparing their sequences to those of other organisms in the existing database of sequence information. In order to exploit the sequence-homology approach most efficiently, facile methods for deducing the function of cloned genes must be developed.

Although it is currently possible to make "pseudo mutations" by transforming plants with an antisense (backward) version of a cloned gene that obliterates the expression of the endogenous gene, this approach involves substantial delay because of the time required to produce the transgenic plant. A method based on the production of a comprehensive collection of insertion or deletion mutations that can be screened by DNA sequence-based techniques, such as the polymerase chain reaction, would thus offer long-term advantages.

These and many other anticipated outcomes from the sequencing projects will have profound effects on the growth of knowledge in particular areas of biology during the next two decades. Dissection of the molecular components of the cellular machinery and the factors that control gene expression, pathogen and pest resistance, morphogenesis, developmental timing, and pattern formation will benefit most directly because they are amenable to dissection by genetic approaches. Fortunately, these topics include some of the areas of plant biology where the gaps in knowledge are extensive and, therefore, where there is great potential for the discovery of new biological principles.

The following essay by Neil Hoffman provides an example of the use of sequence homology to open a new initiative in plant cell biology. Although the gene described in his essay was identified before

large-scale sequencing of plant genes was initiated, the method of identification and analysis was directly analogous to finding the sequence of a gene in a genome database. Amie Franklin, a student in Neil's laboratory, serendipitously identified a cDNA clone that showed significant sequence homology to a gene whose product was known to be involved in transport of proteins into the endoplasmic reticulum of animals. Franklin and Hoffman made the conceptual leap to the idea that the plant protein might be a component of the mechanism responsible for insertion of proteins into chloroplast membranes. Postdoctoral fellow Marsha Pilgrim has created transgenic *Arabidopsis* plants that express low levels of the protein, allowing this hypothesis to be tested in vivo. Now that the plant genome projects are producing large amounts of public sequence information, the need for serendipity has been reduced, but the conceptual leap remains essential.

A Short Report by Winslow Briggs describes the use of genome technology to facilitate the identification of gene products involved in blue-light photoreception. Postdoctoral associates Emmanuel Liscum and Paul Oeller in Briggs's lab have implemented a novel technique for obtaining molecular markers that map sufficiently close to an important mutation so that the corresponding gene can be cloned on the basis of its proximity to the markers. The same approach is currently being used by postdoctoral fellows Robin Buell, Iain Wilson, Luc Adam, and Yoko Nishizawa in Shauna Somerville's laboratory for the isolation of *Arabidopsis* genes involved in disease resistance. As noted above, in the future this process, "chromosome landing," will benefit greatly from the detailed genetic information to result from the genome project.

—*Chris Somerville*

Protein Targeting by the Chloroplast Signal Recognition Particle

by Neil E. Hoffman

Neil Hoffman

All organisms are faced with a common logistical challenge: how to move proteins from their sites of synthesis to their sites of action. Proteins must be able to cross through or insert into membranes. As cells contain multiple compartments, mechanisms have evolved to ensure targeting specificity. What allows a protein to move through one membrane but be retained by another? How is a protein inserted into a membrane? How is a protein specifically

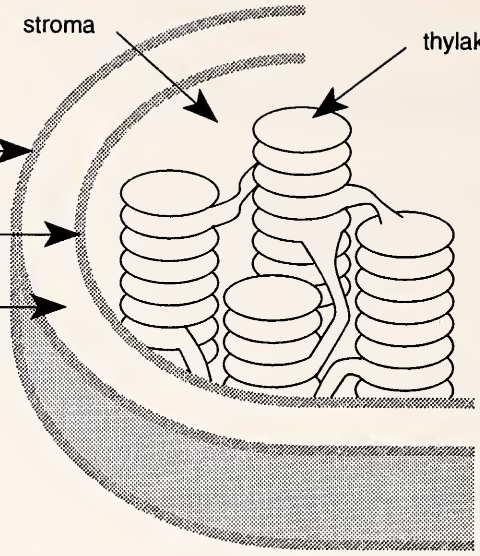

Fig. 1. Cutaway segment of a chloroplast. The thylakoids are membraneous sacs, configured in interconnected stacks; the thylakoid membrane encloses the thylakoid lumen.

targeted to a particular membrane? My lab is trying to answer these questions using proteins targeted to the membranes of the chloroplast.

The chloroplast is the plant cell's most highly compartmentalized organelle (see Fig. 1). It possesses three membranes: an outer envelope membrane, an inner envelope membrane, and the thylakoid membrane. Three aqueous compartments also exist: the intermembrane space, the stroma (between the inner membrane and the thylakoid membrane), and the thylakoid lumen. The thylakoid membrane is densely packed with the proteins that carry on the light reactions of photosynthesis. Some of these proteins degrade rapidly and so must be replaced. Furthermore, the size of the photosynthetic apparatus is continually changing to adapt to the prevailing light conditions. Thus, how proteins are targeted to and inserted into the thylakoid membrane is an important aspect of the regulation of photosynthesis.

The intellectual framework for understanding protein sorting was proposed nearly twenty years ago by Gunter Blobel. He envisioned that sorting information is specified within a protein's sequences of peptides, and that targeting is controlled by receptors on the target membrane surface that bind the sorting signals of the peptides. Movement of the protein through or insertion into the membrane was postulated to occur within membrane channels. Blobel's model has largely been substantiated by intensive studies on protein secretion in mammalian cells. Secreted proteins are synthesized in the cytoplasm and contain a targeting signal, termed the signal sequence. The signal sequence of secretory proteins interacts with a cytoplasmic particle termed the signal recognition particle (SRP). The SRP travels to and binds to a receptor on the surface of the endoplasmic reticulum (ER). The secretory protein it carries is thus moved to the ER membrane surface. The protein is inserted into a channel where it is either moved across the membrane or retained within. The SRP is then released to retrieve another cargo.

Our studies have largely focused on the targeting of the major antenna protein of the chloroplast's thylakoid membrane. This protein is called LHCP, light harvesting complex protein. Like most other chloroplast proteins, LHCP is synthesized in the cell's cytoplasm, and

is subsequently routed to the chloroplast by a sorting signal within its peptide sequences called the transit peptide. The transit peptide binds to a receptor on the surface of the outer envelope membrane and initiates the movement of LHCP through both envelope membranes. Further steps in the transporting of LHCP to the thylakoid membrane have been studied elsewhere using in vitro assays. For example, radiolabeled LHCP was found to integrate correctly into thylakoid membranes when added to either isolated chloroplasts or isolated thylakoid membranes. In the latter case, the addition of stroma and the energy carrier ATP was also found to be necessary. Our recent work has led us to the identification of at least one stromal component required for LHCP targeting and the realization that the energy carrier required for the reaction is not ATP but GTP.

Role of Chloroplast 54p in Targeting of LHCP

Amie Franklin, a Stanford student who recently completed her doctorate in my laboratory, discovered that chloroplasts contain a protein homologous to the 54 kD subunit of mammalian SRP. Cytoplasmic 54p is the subunit of SRP that binds to the signal sequence of proteins in mammalian cells. It also binds and hydrolyzes GTP; this hydrolysis step (the release of a phosphate group with a concomitant release of energy) is required for SRP to perform multiple rounds of targeting. Given this well-known role of 54p in the targeting of mammalian membrane proteins, then, we examined whether chloroplast 54p (cp54p) could play a role in the targeting of LHCP.

From previous in vitro studies by others, it was determined that LHCP integration requires a nucleoside triphosphate as its source of energy. It was generally accepted that the specific nucleotide required was the common energy carrier ATP. However, in these former studies, low-molecular-weight compounds, including GMP and GDP, that could give rise to GTP in the presence of ATP, were not removed from the reactants used in the assay. But when we removed the endogenous nucleotides from the assay, we observed that GTP was over ten times more effective than ATP in supporting LHCP integration. Using non-hydrolyzable analogs of GTP, we determined that LHCP integration required GTP hydrolysis. Furthermore, using a GTP analog that irreversibly binds to and inactivates guanine-binding proteins, we obtained evidence that the GTP-requiring step occurs when LHCP is in the stroma. These results were consistent with an involvement of cp54p in LHCP integration. We have since confirmed that purified cp54p binds and hydrolyzes GTP (Li and Hoffman, unpublished results).

In collaboration with Ken Cline and Ralph Henry (University of Florida), postdoctoral fellow Xingxiang Li and I found compelling evidence that chloroplast 54p is required for LHCP targeting (*Proc. Nat.*

Acad. Sci. USA 92, 3789–3793, 1995). The Cline lab determined that despite the fact that LHCP is a very hydrophobic (poorly soluble) protein, it is targeted to the thylakoid through the stroma. In experimental aqueous solution, LHCP aggregates and precipitates. What then keeps LHCP soluble during its transit through the stroma? Cline observed that LHCP remained soluble if mixed with stroma. This observation prompted the group to speculate that LHCP interacted with a molecular chaperone upon its import into the chloroplast. The most likely candidates were the heat shock proteins HSP60 and HSP70, as both are abundant in all cellular compartments, including the chloroplast, and are known to play a role in the targeting of proteins to the ER and mitochondria. By immunodepleting HSP70 or HSP60 from the stroma, the Cline lab tested whether either protein was the stromal factor that kept LHCP soluble. Surprisingly, removal of either one from the stroma had no adverse effect on the solubility of LHCP. Likewise, the removal of either protein had no deleterious effect on the integration of LHCP into the thylakoid membrane. In contrast, we, now working with the Cline lab, found that when cp54p was immunodepleted from the stroma, LHCP precipitated. Furthermore, we observed a direct interaction between LHCP and cp54p by chemical crosslinking. These two lines of evidence strongly indicated that cp54p is the factor that maintains the solubility of LHCP during its transit through the stroma. In addition, we observed that LHCP was not integrated into thylakoid membranes when assayed using stroma depleted of cp54p. This latter result indicates that the complex formed between LHCP and 54p is an intermediate in the targeting pathway of LHCP.

To further investigate the function of cp54p, postdoctoral fellow Marsha Pilgrim generated transgenic *Arabidopsis* plants that contain reduced levels of this protein. These transgenic plants produce leaves that are initially pale yellow but slowly turn green with time. This behavior is consistent with a role for cp54p in targeting of LHCP. LHCP binds up to 50% of the leaf chlorophyll and is normally a very stable protein. If the efficiency of LHCP integration into the membrane is reduced, we envision that leaves will initially contain reduced levels of the antenna protein but through time will accumulate normal levels. This hypothesis is currently being tested. The plants containing reduced levels of cp54p will also be used to test whether other thylakoid proteins require cp54p for their insertion into the membrane.

Structure of Chloroplast SRP (cpSRP)

The SRP found in the cytoplasm of eukaryotes consists of an RNA of unknown function, 54p, and five other polypeptides. Prokaryotes contain a simpler form of SRP consisting of an RNA and 54p. As

chloroplast 54p is most closely related to prokaryotic versions of 54p, it is reasonable to expect cpSRP to consist simply of 54p and an RNA species. However, we have been unable to obtain any evidence that a cpSRP RNA exists. Antibodies against cp54p do not immunoprecipitate an RNA species. Furthermore, the in vitro reaction for LHCP integration into thylakoid membranes is extremely resistant to RNase treatments that effectively degrade SRP RNA from other species.

A number of lines of evidence indicate that cp54p is part of a complex. First, in our previous experiments, we used the endogenous form of cp54, which is most likely equivalent to cpSRP. However, when we purified cp54p from *E. coli*, overexpressing the protein, it did not function properly in extracts immunodepleted of the endogenous form. One of several possible explanations is that during immunodepletion the antibodies co-immunoprecipitated additional components of cpSRP required for cp54p activity. Second, isolated cp54p synthesized in *E. coli* or in in vitro translation extracts interacted with LHCP only after being imported into chloroplasts. One possibility is that cp54p is not functional until it interacts with another component present in the stroma. When stroma is run on a gel filtration column, cp54p elutes as a 200-kD species. Using an immunoaffinity purification procedure, we isolated a complex consisting of 54p and one additional 43 kD protein. It may be that other components of the complex are eluding detection. Alternatively, the complex may be a tetramer comprised only of the two proteins, 54p and 43p. We have sequenced several peptides from 43p, and we are using this information to obtain its cDNA. Future experiments will address whether 43p is also required for targeting of LHCP, the nature of the interaction between 43p and 54p, and whether the two proteins interact with other factors. According to our present working model, cpSRP lacks an RNA species. An interesting possibility is that 43p substitutes for the RNA.

Future Prospects

The discovery of the cpSRP has provided an excellent opportunity to unravel the biochemical events involved in the insertion of proteins into the thylakoid membrane. Major questions that remain to be addressed include whether other factors besides 54p and possibly 43p are required for cpSRP function, whether other proteins besides LHCP are delivered to the thylakoid membrane by cpSRP, and how proteins are specifically targeted to the thylakoid.

Based on the role of eukaryotic SRP in the cytoplasm, we would expect cpSRP to bind a receptor in the thylakoid membrane, and the cargo (LHCP or other membrane proteins) to be inserted into the membrane via a channel (see Fig. 2). In this scenario, cpSRP would function as a pilot guiding the cargo from one destination to another.

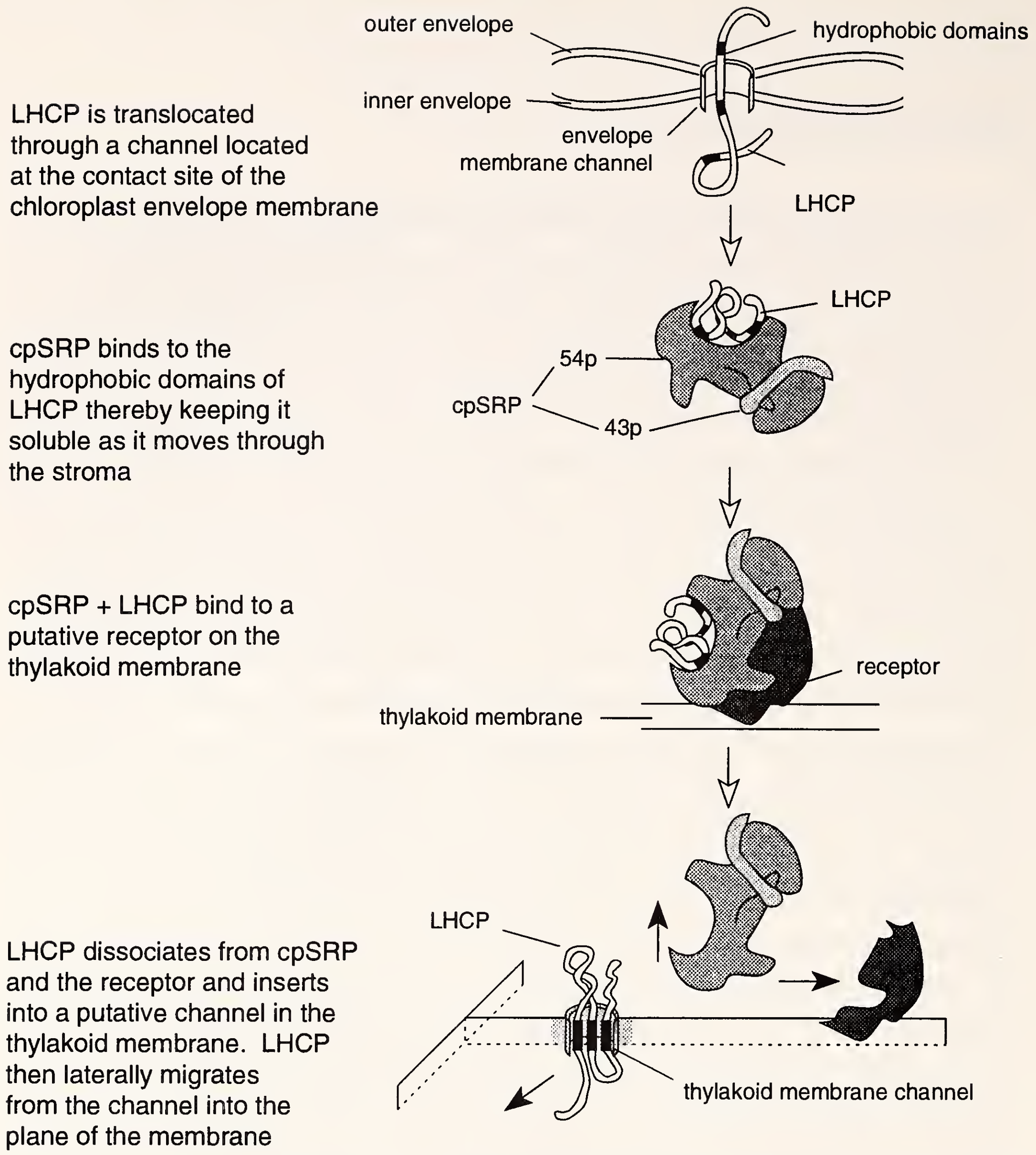

Fig. 2. Speculative view of the role of cpSRP in targeting LHCP to the thylakoid membrane.

Alternatively, the cargo protein itself may contain the sequences that interact with the putative receptor in the thylakoid membrane. In this case, cpSRP would function simply as a chaperone.

How is the cargo specifically delivered? The ability of a hydrophobic protein such as LHCP to pass through two envelope membranes yet be retained by the thylakoid is intriguing. We know that the transit peptide initiates movement of thylakoid proteins across the envelope membranes. However, the signals in envelope proteins that allow their retention by the envelope are unknown. Likewise the thylakoid targeting information in LHCP remains unknown in spite of attempts to define it by ourselves and others. For proteins targeted to the endoplasmic reticulum, the hydrophobic membrane-spanning regions in the proteins themselves act as a primary signal for targeting. Large regions of an ER protein can be deleted without affecting targeting provided that at least one hydrophobic sequence is left intact. If one of these hydrophobic sequences is placed on a non-ER reporter protein lacking such a sequence, the reporter protein can be integrated into the membrane of the ER. This is not the case for LHCP. LHCP spans the membrane in three places. It does not integrate into the

membrane unless all three of its corresponding hydrophobic sequences are intact. Furthermore, none of the three LHCP membrane-spanning regions can localize a non-thylakoid reporter protein to the thylakoid. We interpret these results to mean that the signal for targeting LHCP to the thylakoid membrane is complex, requiring interactions between different regions of the protein. Thus, the signal for insertion of LHCP into the thylakoid membrane appears to differ markedly from the signal sequence of ER proteins. By identifying the cargo dependent on cpSRP for targeting, we hope to gain new insight into the structural features that contribute to targeting specificity.

GTPase activity is often associated with biochemical reactions that ensure specificity. Further study of the GTP requirement for LHCP integration should also provide insight into the mechanism maintaining targeting specificity. This area of research is also facilitated by the discovery of cpSRP, given the likelihood that cp54p is the GTPase required for LHCP integration.

Photoreceptors and the Control of Light-Acclimation Responses in Cyanobacteria

by Arthur Grossman

To absorb light with maximal efficiency a subset of cyanobacteria undergo complementary chromatic adaptation (CCA), a process in which the protein composition of the phycobilisomes, a light-harvesting complex present in cyanobacteria and red algae, responds to the wavelengths of light in an organism's environment. (See *Year Book 92*, pp. 112–117, for a fuller discussion.) In the filamentous cyanobacterium *Fremyella diplosiphon*, this change in phycobiliprotein composition is the result of differential transcription of the *cpcB2A2* and *cpeBA* operons, which encode the blue-pigmented phycocyanin and the red-pigmented phycoerythrin, respectively. (An operon is a transcription unit encoding a cluster of genes.) Transcription from the *cpcB2A2* operon is only activated in red light, while transcription from the *cpeBA* operon is only activated in green light. The process of CCA appears to be controlled by a red/green photoreversible photoreceptor. Understanding photoperception, the signal transduction chain leading from photoperception to gene expression, and the evolutionary relationship between CCA and the perception of light quality in photosynthetic eukaryotic organisms has been a major goal in my laboratory over the past several years.

Arthur Grossman

The primary approach that we have used to elucidate steps in the

signal transduction pathway controlling CCA has involved the generation of mutants that are aberrant in CCA, and the complementation of those mutants to distinguish individual genes.* Until recently, the complementation approach has only been partially successful because of the difficulty in establishing an efficient gene-transfer system for *Fremyella*. Recently, postdoctoral fellow David Kehoe has dramatically improved the gene-transfer technology, and both he and Elena Casey, a graduate student, have begun to define components that are critical for CCA.

Several mutants in CCA have been complemented. One mutant class, designated red mutants, cannot perceive red light. Based on both physiological and biochemical evidence, we would predict that a mutation in the photoreceptor for CCA may result in a red mutant. In early experiments Mike Schaefer and Gisela Chiang complemented one of the red mutants with a gene denoted *rcaC*. The encoded protein RcaC is a response regulator which probably binds to specific regulatory sequences, or promoters, in the photoreceptor to activate genes upon red illumination. Response regulators contain so-called receiver domains in which a conserved aspartate undergoes phosphorylation/dephosphorylation. Only when the aspartates are phosphorylated will the regulator bind to its corresponding promoter(s). RcaC is not a typical regulator since it has two receiver domains, each of which has an aspartate that can be phosphorylated.

Recently, David Kehoe found two other classes of red mutants. One of these involves a region downstream and the other a region upstream of RcaC in the signal transduction chain. Complementation of the mutant upstream (and closer to photoperception) yielded a 4.8-kbp fragment of DNA that contains at least four genes, of which three appear to be in a single operon. These three encode a sensor protein with a histidine kinase domain (ORF II), a response regulator (ORF III), and a protein that has both a histidine phosphorylation domain and a region of 150 amino acids having considerable homology to a domain of phytochrome in higher plants (ORF I). This is exciting, since it is the first identification of a gene in prokaryotes encoding a protein having considerable homology to phytochrome, which plays a vital role in many nonphotosynthetic photoperceptions in higher plants, for example, flowering, seed germination, and stem elongation. It raises the possibility that phytochrome-like molecules also play a role in photoperception in prokaryotic organisms. Since the genetic manipulation of prokaryotes is so much easier than that of eukaryotes, we expect that elucidation of CCA will contribute to an understanding of phytochrome-regulated gene expression in higher plants.

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*In such complementation tests, a normal gene is introduced into a mutant. When the endogenous gene is aberrrant and the introduced gene is not, and function is restored, complementation has occurred and the function of the normal gene has been shown.

Interestingly, the region of the phytochrome-like molecule encoded within the complementing DNA fragment does not, as might be expected, contain the cysteine segment that forms a linkage with the light-absorbing chromophore of phytochrome. However, the fourth gene present on this complementing fragment encodes a product (ORF IV) somewhat similar to a subunit of allophycocyanin, a pigmented polypeptide in the core of the phycobilisome. The latter protein does have a binding site for phycocyanobilin, and while it may be a structural component of the phycobilisome, it may also play a role in photoperception. We are currently determining whether all of the genes on the complementing fragment are needed for CCA and the specific function of each of them. Because of the facility with which we can now genetically manipulate *Fremyella*, we will be able to rapidly define elements controlling CCA, and eventually determine the relationship of this system to the phytochrome system of higher plants.

In addition to the red mutants, we have complemented several other CCA mutants. One of these we call a blue mutant. This mutant cannot suppress the synthesis of phycocyanin in green light; the *cpcB2A2* operon is constitutively expressed. Elena Casey has analyzed this mutant in more detail and has found that this strain can shut off the *cpcB2A2* operon in green light, but only at high-intensity green light. In other words, this strain is less sensitive to green light than is the wild-type strain. The blue mutant has recently been complemented with a 2.6-kbp DNA fragment that encodes a distinct sensor-regulator pair. These findings are important, since almost nothing is known about intensity control of photoresponsive processes. Furthermore, this result provides us with the tools for studying the integration of the wavelength-specific response with an intensity modulator.

Regulation of Plant Respiration

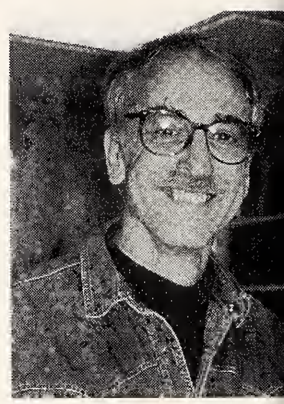
by Joseph Berry

This year we report on a research program that addresses a long-standing puzzle for plant physiologists and biochemists. Plant mitochondria contain two different oxidases (enyzmes capable of reacting with oxygen) which use electrons from the respiratory electron transport chain to form water from molecular oxygen in the plant's respiration cycle.* These oxidases, the cytochrome oxidase and the

*Plant respiration is the biochemical process where the plant's sugars are broken down (oxidized) to release energy (in the form of the energy carrier ATP) for use in the plant's various activities. Photosynthesis builds the food and respiration converts it to the energy needed for metabolism.

alternative oxidase, provide different yields of ATP per electron transported. The alternative oxidase is much less efficient than the cytochrome oxidase. Consequently, the overall efficiency of plant respiration may vary depending on the proportion of electrons used by the two.

Knowledge of this partitioning of electrons and of the biochemical or genetic mechanisms that control it is important for understanding plant respiration. For example, one might propose that it should be possible to increase the efficiency of plant respiration (and consequently the overall yield of plant growth) by decreasing the proportion of respiration going to the alternative oxidase. However, very little is actually known about these matters. The two oxidases are sensitive to different inhibitors, so that inhibitors can be used to show that all plants have some activity of both oxidases. But it is very difficult to use inhibitors to determine what fraction of electron transport is going to each oxidase under steady-state conditions.



Joe Berry

The present research program arose from observations made by Rob Guy while a fellow at the Department of Plant Biology in the mid-1980s. Guy, in collaboration with Marilyn Fogel and Tom Hoering (Geophysical Laboratory) and me, demonstrated that the two oxidases show different preferences for the naturally occurring heavy isotope of oxygen, ^{18}O. Guy proposed that oxygen-isotope discrimination during steady-state respiration could be measured and used (knowing the intrinsic isotope discrimination of the two oxidases) to calculate the partitioning of electron transport. While these measurements were very difficult to make, they provided important information about plant respiration that could not be obtained in any other way.

Over the past few years we have been collaborating with a group at Duke University (including Jim Siedow, Miquel Ribas-Carbo, Sharon Robinson, Dan Yakir, and Larry Giles) to develop new techniques for measuring oxygen-isotope discrimination in both intact plant tissues and isolated mitochondria. (This work was part of Ribas-Carbo's Ph.D. thesis, awarded from the University of Barcelona.) Here, I briefly summarize the findings of the research program.

The original measurements of Guy and co-workers were made by a rather indirect method. Oxygen from the reaction medium was first purified from other constituents of air and then reacted with elemental carbon to form carbon dioxide. The CO_2 was then analyzed for the $^{18}O/^{16}O$ ratio by mass spectroscopy. The major drawback of this method is that it takes approximately one hour to process each sample, making it very difficult to work with unstable biological preparations such as isolated enzymes or organelles. We have now developed a

method based on combined gas chromatography/isotope-ratio mass spectroscopy, which permits measurements to be taken every five minutes with precision similar to that of the original procedure. Measurements can be conducted with reactions in gas phase systems (whole plant organs) or liquid phase systems (biochemical preparations). Measurements with a wide range of materials have been conducted.

One of the most significant findings of our study so far is that the less-efficient alternative oxidase accounts for a significant fraction of respiratory oxygen uptake in many plant tissues. As much as 60% of the respiration in green leaves, for example, is by the alternative oxidase pathway. On the other hand, some tissues such as etiolated (dark-grown) cotyledons have very little if any flux to the alternative pathway. During the greening of cotyledons (upon exposure to light), however, there is a shift to alternative pathway respiration. There is little change in the directly measured activity of the alternative pathway (assayed in the presence of an inhibitor of the cytochrome pathway); hence this shift appears to result from biochemical regulation. Meanwhile, in leaves of plants that fix CO_2 by the crassulacean acid metabolism (CAM) pathway, a substantial change in isotope discrimination occurs, depending on whether the plants are in the acidification (night CO_2 fixation) or the de-acidification (daytime photosynthesis from stored malic acid) phases of the diurnal cycle. Again, this appears to be related to biochemical regulation of the pathways.

The respiratory electron transport pathways reside in the mitochondria. To provide the background for studies with intact tissues, we have initiated a number of biochemical investigations with isolated mitochondria. Experiments conducted with these isolated organelles examine how the pathways respond to chemical changes in the organelle that might occur in vivo. One of the major biochemical factors affecting the kinetics of electron transport is the availability of ADP, the normal energy substrate for one form of (oxidative) phosphorylation. In the absence of ADP (State 4), electron flow via the cytochrome pathway is more restricted than when it is present (State 3). Isotope discrimination is greater in State 4 than in State 3, indicating that a larger proportion of the flow is going via the alternative pathway. Biochemical studies have also identified two effectors, pyruvate and isocitrate, which can stimulate alternative oxidase activity in purified systems. (Effectors are molecules that bind to enyzmes and increase or decrease their activity.) These effectors also increase discrimination during oxygen uptake.

These studies demonstrate responses of the branched electron transport chain of mitochondria that mimic the regulatory responses seen in vivo. However, we do not know at this time what actually

causes the discrimination to change in vivo. Studies of the ATP/ADP ratio or the pool sizes of pyruvate or isocitrate during steady-state metabolism may provide this information.

The physiological significance of alternative oxidase to the efficiency of plant respiration is an interesting and important question. While the function of the alternative pathway is still not known, these studies provide new information on conditions where the plant's regulatory systems seem to require it.

Regulation of metabolic systems is pervasive and is probably essential for the efficient functioning of plants. However, most of these regulatory responses are hidden within the plant cells, invisible to the external observer. The dual oxidase system provides a clear opportunity to study a regulation response.

Short Reports

Olle Björkman: Responses to Long-Term Drought and High-Irradiance Stress in Natural Vegetation

The mechanisms by which plants regulate light energy capture, conversion to sugars, and dissipation in response to environmental stress have continued to be a main focus of my group's work. Much of the work has revolved around the role of non-radiative energy dissipation (NRD) in down-regulating excitation energy to balance the rate of NADPH and ATP consumption by photosynthetic carbon metabolism and to prevent a build-up of excessive and potentially destructive excitation energy at the photosynthetic reaction centers. One project, initiated last year, concerns the ability of the photosynthetic system to cope with very high irradiance under natural conditions that severely restrict, or even preclude, net CO_2 fixation. This is an extension of our previous studies on commercially grown cotton plants and on native vegetation that is regularly exposed to seasonal drought in the native habitat. For the present studies we have chosen the evergreen tree species *Arbutus menziesii* (madrone) and *Quercus agrifolia* (coast live oak), and the winter-deciduous tree *Quercus douglasii* (blue oak), all of which grow fully exposed adjacent to the chaparral in the Jasper Ridge Biological Preserve. Beside having the desirable ecological traits these species proved suitable for the required biochemical analyses.

Our results showed that as the usual summer drought causes water potential to fall (with resultant stomatal closure), the leaves of the two evergreen species cease to take up CO_2, except for a brief period after sunrise when a very low rate of net CO_2 fixation takes place. Hence, throughout the long summer (clear skies and no rainfall), exposed leaves are subjected to very high irradiance levels while little or none of the light energy is used for CO_2 uptake. These conditions are generally thought to promote photodamage. Moreover, unless some of the light energy is used for photophosphorylation, the ATP required for maintenance and repair processes is generated by oxidative phosphorylation, which depletes scarce, stored carbon resources.

Data obtained to date indicate that,

although the efficiency of photosynthetic electron transport in full sunlight under these non-CO_2-fixing conditions is considerably lower than at times of the year when water relations are favorable, the rate of such electron flow is still substantial. The results also show that the adenylate energy charge in full sunlight is very high, suggesting that photophosphorylation occurs at a significant rate. Fluorescence quenching analyses show an extraordinarily high level of nonphotochemical quenching in these leaves accompanied by an extremely high degree of violaxanthin deep oxidation. This indicates the presence of a large transthylakoid proton gradient and a very high rate of nonradiative energy dissipation. Surprisingly, predawn fluorescence measurements show that the intrinsic efficiency of photosystem II photochemistry is quite normal, indicating that there is no sustained photodamage. We tentatively conclude that, even under these extreme photoinhibitory conditions, nonradiative energy dissipation, presumably with a high rate of repair (such as of the D1 protein), prevent any significant net photodamage to the leaves of these drought-stressed plants.

Winslow Briggs: Transduction of Blue-Light Signals in Phototropic Responses

The phototropic response of seedlings is important for the rapid orientation of newly germinated plants to light, essential for photosynthesis and the survival of the young plant. We have recently reported the isolation and characterization of eight mutants in *Arabidopsis* which are severely impaired or lack this directional growth response to blue light. These mutants fall into four genetic loci, designated *nph1*, *nph2*, *nph3*, and *nph4*, where *nph* stands for *n*on-*p*hototropic *h*ypocotyl. The *nph1* locus probably encodes a 120-kD plasma membrane protein that becomes rapidly phosphorylated in response to blue-light irradiation, either in vivo or in vitro in the presence of ATP and Mg^{++}. We have previously shown this plasma membrane protein to be involved in the phototropic response. Physiological and biochemical evidence strongly suggest that it may be the photoreceptor, although this hypothesis awaits a definitive test. The second and third loci encode proteins that are likely downstream from the photoperception event, since although the plants fail to respond to unilateral light with a normal growth curvature, they show normal amounts of the putative photoreceptor protein and normal phosphorylation. The fourth locus encodes a protein essential both for phototropism and for gravitropism—the directional response of growing plant organs to gravity—and hence is likely still farther downstream from the putative photoreceptor.

We have recently been using a technique known as Amplified Fragment Length Polymorphism (AFLP) to generate DNA fragments that are genetically linked to a given *nph* locus. We have had considerable success identifying fragments linked to the *nph1* locus. Two such fragments, each within 0.3 centimorgans of the *nph1* locus and on opposite flanking regions, have been subcloned and are being used to isolate genomic DNA containing the wild-type *NPH1* gene. One of these fragments identifies two overlapping *Arabidopsis* Yeast Artificial Chromosomes (YACs) that have been mapped to the same region of the genome where classical genetics has indicated the *NPH1* locus resides. We are hopeful that one of these YACs, or an adjacent overlapping YAC, will contain the *NPH1* gene so that we will finally be able to definitively address the nature of the 120-kD phosphoprotein it encodes. Isolation and characterization of the

NPH1 gene will also open up approaches to a wide range of physiological and biochemical questions.

On a related front, there has been a recent report that a carotenoid, zeaxanthin, might be the photoreceptor chromophore for phototropism. Since this carotenoid is normally located in the chloroplast, and our own evidence suggested that the photoreceptor is located in the plasma membrane, we produced maize seedlings that had been depleted of virtually all carotenoids either by chemical or genetic means, and tested them for phototropic sensitivity and for blue-light–induced phosphorylation. In every case, phototropism and blue-light–induced phosphorylation were completely normal. Hence we conclude that zeaxanthin cannot be the photoreceptor chromophore in maize.

Emmanuel Liscum isolated and characterized the *nph* mutants of *Arabidopsis* and introduced the AFLP technology into our laboratory. Paul Oeller has carried on with the AFLP work on *nph1* and is doing the chromosome hopping with that locus, while Liscum has begun using AFLP with other mutants in the pathway. Julie Palmer, following some initial work by Katherine M. F. Warpeha, carried out the carotenoid investigations.

Winslow Briggs (right) with postdoctoral fellows Mannie Liscum (left) and Paul Oeller.

Chris Field: Ecosystem Responses to Global Change

To test our understanding of the global scale controls on biospheric production and decomposition, the global modeling group (Jim Randerson, Carolyn Malmstrom, Matthew Thompson, and Anne Ruimy) has been examining a ten-year record of climate and satellite vegetation data, comparing the predictions from our CASA (Carnegie Ames Stanford Approach) model with estimates inferred from the concentration of CO_2 in the atmosphere. The group finds that though the model does not perfectly predict variations in atmospheric CO_2, it does a good job of estimating productivity variations in test regions and is increasingly useful for estimating productivity over the time scale of months to a decade. In other work with the now standardized and widely distributed CASA model, people in the lab are exploring the role of the biosphere in recent increases in the magnitude of the annual oscillation of atmospheric CO_2 concentration and are testing the hypothesis that the concentration and dynamics of ^{13}C in the atmosphere confirms the presence and size of a 1–2 gigaton per year carbon sink in the terrestrial biosphere. New projects just getting under way include efforts to develop new models of plant respiration and biomass allocation as well as efforts to make CASA appropriate for operation within an atmospheric general circulation model (GCM).

The ecosystem-scale experiments with elevated CO_2 at Stanford's Jasper Ridge Biological Preserve continue to emphasize the importance of CO_2 on water relations. Elevated CO_2 leads to decreased leaf conductance, which leads to increased soil moisture (Art Fredeen, Chris Lund, Jim Randerson). This increase in soil moisture has a number of consequences. One potentially important one is increased nitrogen availability for plants and increased plant uptake of nitrogen (research by Bruce Hungate at UC

Berkeley). This is accompanied by increased soil respiration, which tends to suppress the potential for increased photosynthesis to lead to increased soil carbon. Another consequence is altered plant species composition, with large increases in the abundance of the plant species that are best able to use water reserves late in the winter-spring growing season (Nona Chiariello, Chris Field).

Outside the main areas of emphasis, N. Michele Holbrook completed her Ph.D. thesis on the role of plant water status in controlling leaf water status and leaf conductance. Holbrook's thesis work uncovered surprisingly large gradients of water stress between stems and leaves, and it confirmed, in the most direct experiments to date, that water in plants can be under substantial tension (negative pressures), a hypothesis subjected to recent challenges. In elegant experiments with grafts between tomatoes that can and cannot make normal levels of the plant hormone abscisic acid (ABA), Holbrook demonstrated that, contrary to many recent claims, ABA is not necessary as a messenger to inform shoots that part of the root zone is experiencing drought.

Shauna Somerville: Identifying Disease Resistance Genes

If a host plant is not able to distinguish a pathogen from the various benign or beneficial microbes in the environment and defend itself, then the host will succumb to disease. Resistance genes are thought to play a central role in pathogen recognition and to activate defense mechanisms either directly or indirectly. Each pathogen isolate is recognized by the gene product of a distinct resistance gene. Thus, for well-characterized plants like wheat, more than one hundred disease resistance genes have been described.

We are particularly interested in the *Arabidopsis* genes encoding resistance to the powdery mildew disease, which is caused by the obligate fungal pathogen *Erysiphe cichoracearum*. Previously we identified six powdery mildew–resistant *Arabidopsis* accessions from a screen of 59. In cooperation with Richard Oliver (University of East Anglia, U.K.), we have screened an additional 200 accessions of which roughly 25% are resistant to powdery mildew disease. This observation indicates that significant natural diversity for powdery mildew resistance exists in *Arabidopsis*.

To date, we have identified five distinct powdery mildew resistance genes in *Arabidopsis* and placed these genes on the genetic map. Two genes, *RPW2* and *RPW3*, appear to encode contrasting resistance mechanisms. Disease resistance is recessive to susceptibility at the *RPW3* locus, while resistance at the *RPW2* locus is semidominant to the susceptibility. Currently, precise map positions for these two genes are being determined. During the next year, two independent strategies for cloning *RPW2* and *RPW3* will be pursued. One strategy is positional cloning. The second is the candidate gene approach in which anonymous cDNA clones with a leucine-rich repeat sequence motif will be mapped relative to *RPW2* and *RPW3*. Six of eight cloned plant disease resistance genes contain a leucine-rich repeat motif. Thus, the latter approach to cloning *RPW2* and *RPW3* is based on the assumption that most disease resistance genes contain a leucine-rich repeat motif.

Chris Somerville: Morphogenesis in *Arabidopsis*

In higher plants, the developmental processes that bring about the spatial arrangement of differentiated cells and tissues depend upon unknown mechanisms that interpret cellular cues defining the identity of a cell and that translate this information into the physical orientation of the cell plate during cell division. Thus, for instance,

initiation of secondary root formation involves a shift in the plane of cell division away from the long axis of the root to an orientation that is essentially perpendicular to the main axis. In order to identify gene products that control and mediate this phenomenon, we are characterizing mutants of *Arabidopsis* that exhibit altered patterns of cell division. Since the ability to control the plane of cell division is thought to be required for viability, we are utilizing mutations that are "leaky" or are expressed only under certain conditions (e.g., at high temperature or on media containing protein-destabilizing agents) or in specialized tissues such as flower petals or early embryos. Postdoctoral fellow James Zhang has recently isolated a mutation called *twn2* that appears to influence the orientation of the first few cell divisions following fertilization. The gene has been cloned by insertional mutagenesis and is currently being characterized to determine when and where it is expressed and what function its gene product has. Several other potentially informative mutations are being characterized in preparation for the isolation of the corresponding genes by map-based cloning.

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Personnel

Research Staff

Joseph A. Berry
Olle E. Björkman
Winslow R. Briggs, Director Emeritus
Christopher B. Field
David C. Fork[1]
Arthur R. Grossman
Neil E. Hoffman
Christopher R. Somerville, Director
Shauna C. Somerville

Visiting Investigators

Ruth Alscher, Virginia Polytechnic Institute and State University, NSF Fellow[2]
Pierre Broun, Monsanto Fellow
Steven Lindley, Duke University

Postdoctoral Fellows and Associates

Luc Adam, NSF Research Associate

Kirk E. Apt, NSF Research Associate
Thomas R. Berkelman, NIH Research Associate
Robin Buell, USDA Fellow
Gregory D. Colello, NASA Research Associate
John P. Davies, USDA Research Associate
Deane Falcone, NSF Research Associate
Arthur F. Fredeen, Mellon Fellow[2]
Wei Fu, NASA Research Associate
David M. Kehoe, NSF Fellow
Xingxiang Li, NIH Research Associate[3]
Emmanuel Liscum, NSF Research Associate
Christiane Nawrath, NSF Research Associate[4]
Michelle Nikoloff, DOE Research Associate
Krishna Niyogi, LSRF Fellow
Paul Oeller, NSF Research Associate
Joseph P. Ogas, NSF Fellow
Marsha Pilgrim, NASA Fellow
Yves Poirier, DOE Research Associate[5]
Rakefet Schwarz, International Human Frontier Science Fellow[6]
Wayne Stochaj, NSF Fellow
Susan S. Thayer, NSF Research Associate
Simon Turner, EMBO Fellow
Fitnat H. Yildiz, Carnegie Fellow
James Zhang, DOE Research Associate

Predoctoral Fellows and Associates

Stefan Berggren, University of Agricultural Science, Uppsala, Sweden[7]
Steven Reiser, Michigan State University

Students

Elena M. Casey, Stanford University
Sean Cutler, Stanford University
M. Elise Dement, Stanford University
Amie E. Franklin, Stanford University[2]
Stewart Gillmor, Stanford University
Claire Granger, Stanford University
N. Michele Holbrook, Stanford University[2]
Catharina Lindley, Stanford University
Chris Lund, Stanford University
Carolyn Malmstrom, Stanford University
Margaret Olney, Stanford University
Patti Poindexter, Stanford University
John Quisel, Stanford University
Jim Randerson, Stanford University
Seung Rhee, Stanford University
Amy Verhoeven, University of Colorado[2]
Dennis Wycoff, Stanford University[8]

Support Staff

Ann Blanche Adams, Laboratory Technician
Cesar R. Bautista, Horticulturist
Mike Blaylock, Laboratory Assistant
Frank Burkholder, Laboratory Assistant[9]
Catherine Cassayre, Laboratory Assistant[10]
Sara Chun, Laboratory Assistant[11]
Julie M. des Rosiers, Laboratory Technician
Nadia Dolganov, Research Associate
Jane S. Edwards, Administrative Assistant
Celeste Falcone, Photographer[12]
Glenn A. Ford, Laboratory Manager
Cyril D. Grivet, Senior Laboratory Technician
Nat Hawker, Laboratory Technician[13]
Justin Holl, Laboratory Technician[14]
Geeske Joel, Laboratory Technician
Barbara A. March, Bookkeeper
Sylvia Martinez Straumann, Laboratory Assistant
Ann D. McKillop, Laboratory Technician[15]
Laura McLarty, Laboratory Assistant[16]
Barbara E. Mortimer, Laboratory Technician
Thong Nguyen, Laboratory Assistant[17]
Frank Nicholson, Facilities Manager
Marc Nishimura, Laboratory Technician[18]
Pedro F. Pulido, Maintenance Technician
Melani Reddy, Laboratory Assistant[19]
Larry D. Reid, Maintenance Technician
Connie K. Shih, Senior Laboratory Technician
David Smernoff, Research Assistant[20]
Mary A. Smith, Business Manager
Colby Starker, Laboratory Technician[21]
Paige Thomas, Laboratory Assistant
Thang Truong, Laboratory Assistant[22]
Yufeng Wang, Laboratory Assistant[23]
Rudolph Warren, Maintenance Technician
Aida E. Wells, Secretary
Brian M. Welsh, Mechanical Engineer
Howard Whitted, Support Engineer
Sunia Yang, Electrical Engineer

* * *

[1]Retired, June 30, 1995
[2]To December 31, 1994
[3]To November 30, 1994
[4]To February 15, 1995
[5]To January 18, 1995
[6]From August 17, 1994
[7]From April 1, 1995
[8]From September 26, 1994
[9]To July 11, 1994
[10]From June 19, 1995
[11]From June 26, 1995
[12]To November 4, 1994
[13]From January 1, 1995
[14]From June 29, 1995
[15]To November 28, 1994
[16]From September 7, 1994
[17]From November 17, 1994
[18]From September 22, 1994
[19]From June 26, 1995
[20]To August 31, 1994
[21]From February 6, 1995
[22]To September 30, 1994
[23]To June 30, 1995

Geophysical Laboratory

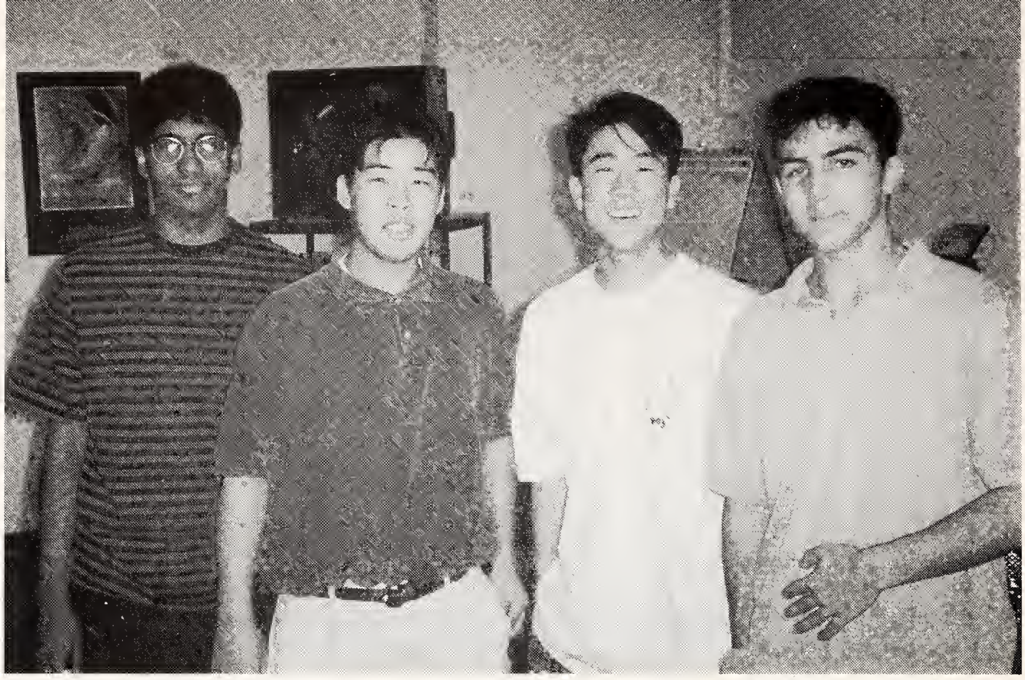
Doug Rumble using the CO_2-laser oxygen isotope microprobe

Members of the Geophysical Laboratory, June 1995. First row, left to right: Ed Hare, Frank Press, Yingwei Fei, Doug Rumble, Dave Virgo, Dave Mao, Neil Irvine, Charles Prewitt, Joe Boyd, Larry Finger, Bjørn Mysen, John Frantz, Bob Hazen, Marilyn Fogel, Rus Hemley, Ron Cohen. Second row: Pedro Roa, Paul Meeder, Julie Kokis, Alessandra Barelli, Carmen Aguilar, Sue Schmidt, Shaun Hardy, Dave George, Kathleen Kingma, Lucia Lazorova, Iris Inbar, Alex Goncharov, Jinfu Shu, Glenn Goodfriend, Nabil Boctor, Guoyin Shen, Mark Wah. Third row: Alison Brooks, Lawrence Patrick, Pablo Esparza, Chris Hadidiacos, Jack Almquist, Merri Wolf, Larry Solheim, John VanDecar, Carol Lynch, Chang-Sheng Zha, Igor Mazin, Viktor Struzhkin, Joshua Weitz. Top row: Maddury Somayazulu, Steve Coley, Peter Lazor, Michael Walter, John Ferry, David Bell, John Straub, Liz James, Ming Li, Mark Kluge, David Teter, Beverly Johnson.

Director's Introduction

During the past five years, several members of the Geophysical Laboratory staff have been part of a team planning for geoscience beamlines at the new Advanced Photon Source (APS) at Argonne National Laboratory, Illinois. The APS is a "third-generation" synchrotron light source (generating electromagnetic radiation ranging from x-rays through the infrared), now under construction and scheduled to begin operation in 1996. Our involvement at APS and similar new synchrotrons in France and Japan is a natural development stemming from our research at other facilities, including the National Synchrotron Light Source, Cornell High Energy Synchrotron Source, Stanford Synchrotron Radiation Laboratory, and the Photon Factory in Japan. APS will generate x-ray beams that are sharper, brighter, more energetic, and more stable than their predecessors, thus allowing experiments to be performed that require these special characteristics.

For a synchrotron to produce light, a beam of positrons (positively charged electrons) must be generated and accelerated to the required energy. In the APS design, electrons are accelerated in a linear accelerator to 200 MeV (million electron volts) and beamed onto a tungsten wafer, creating electron-positron pairs. The positrons are separated magnetically and accelerated further to 450 MeV, collected in an accumulator ring, and injected into a booster synchrotron where their energy is raised to 7000 MeV. They are then injected into the 1104-meter storage ring, where they orbit and generate electromagnetic radiation when passing between bending, undulator, or wiggler magnets located at intervals around the storage ring. Compared to existing synchrotron sources, the APS will provide a thousandfold increase in x-ray brilliance.



Left to right: Student interns Arun Vemury, John Kim, Billy Lee, and David Stockman.

In the late 1970s, hardly anyone in the geoscience community knew how a synchrotron facility could be used for relevant experiments, to say nothing of how one might gain access to a facility constructed and used primarily by physicists. But by 1980 several people saw the potential for exciting new applications, and now geoscientists around the world have become significant participants in this major scientific enterprise. This came about through persistence in a range of activities—learning about the organization of synchrotron initiatives, planning workshops and presentations at scientific meetings, producing reports through the National Academy of Sciences/National Research Council and other organizations, developing research projects and submitting proposals for funding to granting agencies, and, finally, publishing research results in leading scientific journals.

Today, the availability of synchrotron radiation makes it possible to attempt experiments that could not be performed using any other kind of radiation source. It brings together people from many different disciplines to work on common instrumental, computational, and analytical problems even as it encourages scientific collaboration between, for example, earth scientists and materials scientists.

The Geophysical Laboratory's past involvement in research using synchrotron facilities has been primarily at the National Synchrotron Light Source, Brookhaven, New York. There we have been primarily responsible for constructing and operating the X17C beamline, which makes use of the superconducting wiggler, a device that produces x-radiation with much higher energies than are available on the standard bending-magnet beamlines. We are also major participants in the U2B infrared beamline, which has been particularly useful in our research on hydrogen at high pressure and which is available for infrared experiments on amounts of material too small for examination using standard infrared spectrometers. The accompanying essay by Russell Hemley illustrates how access to these beamlines has been essential for our studies of hydrogen at high pressure.

The Geophysical Laboratory and others from the geoscience and environmental-science communities are represented at APS by the Consortium for Advanced Radiation Sources (CARS), based at the University of Chicago. CARS was formed in 1989 to provide the administrative and technical support for construction of experimental beamlines, and is composed of three subunits, GeoSoilEnviroCARS, BioCARS, and Chem/MatCARS, each of which will build and operate distinct beamline facilities. GeoSoilEnviroCARS is composed of representatives of the entire U.S. community of earth scientists who utilize synchrotron radiation in their research. This group has been funded by the National Science Foundation, the Department of Energy, and the Keck Foundation to construct a national user facility at the APS, with the goal of conducting frontier research on the structure and composition of earth materials. These studies will provide fundamental new information on such important problems as the deep structure and composition of the Earth, the formation of economic mineral deposits, the cycles and fate of toxic metals in the environment, and the mechanisms of nutrient uptake from soils.

Although a number of different kinds of experiments are possible using these facilities, including x-ray absorption spectroscopy and x-ray microprobe analysis, we in the Center for High Pressure Research are particularly interested in experiments where samples are squeezed between opposing anvils of diamond or tungsten carbide to create high pressure. At the same time, it is often desirable to heat the sample to hundreds or thousands of degrees and to calibrate the simultaneous high pressure and temperature while measuring a sample's physical and chemical properties. This is not an easy task, requiring that very intense synchrotron radiation be directed onto the sample in a diamond cell and/or on a tiny spot several micrometers in diameter while being heated by a laser, producing diffraction patterns or absorption/emission spectra. Synchrotron high-pressure experiments were first carried out in the early 1980s and are now recognized as one of the most important scientific applications of synchrotron radiation. It is a happy coincidence that the Center for High Pressure Research, located at the Geophysical Laboratory, State University of New York, Stony Brook, and Princeton University, was organized at just the time that synchrotron facilities became readily available.

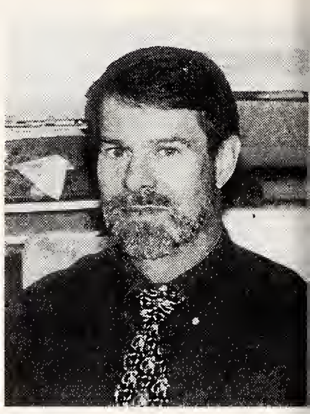
These national and international facilities offer the latest and best opportunities for conducting experiments on the atomic structure and chemical compositions of a wide range of materials, including minerals and their synthetic analogs. In these difficult times for science funding we are fortunate in having unprecedented access to the new synchrotron radiation sources that represent the leading edge in technology for the study of these materials.

—*Charles T. Prewitt*

Order-Disorder in Materials at High Pressure

by Robert M. Hazen

Pressure plays a central role in the structure and energetics of materials in Earth's deep interior, and it provides a powerful means for probing atomic interactions in solids. In a recurrent historical pattern, however, technically difficult experiments on phenomena at high pressure often lag far behind detailed high-temperature investigations. Neptunists of the eighteenth century—believers that crustal rocks were formed by the agency of water—knew of the high-temperature decarbonation of limestone and used the associated room-pressure data in their attempts to disprove the igneous origin of basalt in contact with limestone. It was not until 1806 that Sir James Hall bolstered the opposing plutonist position by demonstrating that high pressure stabilizes carbonate at high temperature, so that hot intrusive basalt and limestone can coexist. Similarly, almost two centuries later, data on mineral and rock melting, rock mechanical properties, crystal structures, and solid-solid phase equilibria are often obtained at high temperature long before high-pressure studies commence.



Robert Hazen

A similar situation exists in mineralogical studies of order-disorder phenomena, which have long been viewed as keys to understanding the thermal history of rocks. Order-disorder reactions include a variety of atomic-scale phenomena that affect a crystal's ideal regularity. Each atom in an ideally ordered crystal occurs in a specific position and chemical environment—a crystallographic site that repeats identically, over and over throughout the solid. This regularity may be disrupted by a wide variety of phenomena, including displacements of an atom from its ideal position (vibrational and rotational disorder), substitution of incorrect atoms (defects and substitutional disorder), and transfer of electrons (electronic disorder).

Pressure affects all of these types of order-disorder to some extent. Application of pressure, for example, generally decreases the magnitude of atomic vibrations that displace all atoms from their ideal positions. Increased pressure also inhibits molecular rotation, which contributes to positional disorder in some molecular crystals, including buckeyballs, solid hydrogen, and solid methane. But although such phenomena have been studied extensively as a function of temperature and composition, until recently they have not been investigated at high pressure. Our work here at the Center for High Pressure Research suggests that pressure may play a significant, and in some cases

dominant, role in the order-disorder behavior of minerals.

Of primary importance in understanding rock-forming minerals is substitutional disorder, which results from the interchange of two different atoms over two or more crystallographic sites. In the classic example of copper-gold metal alloys, disordered structures have a random distribution of copper and gold atoms, whereas ordered variants feature strict alternation of Cu and Au atoms. Similarly in many rock-forming minerals, pairs of similar metal atoms, such as aluminum and silicon in feldspars, nickel and magnesium in olivines, or calcium and iron in carbonates, display wide ranges of ordering, from fully ordered to fully disordered variants.

An important feature of substitutional order-disorder reactions is that any change in the degree of substitutional disorder requires atoms to move from one site to another in the structure, generally over a distance of several atomic diameters. This situation contrasts, for example, with changes in vibrational disorder, where only a very small shift in atomic location is required. Consequently, an energy barrier must be overcome such that transitions in the degree of substitutional order are often quite sluggish. The tendency of minerals to "freeze in" a state of substitutional order-disorder allows geologists, who measure the ordered state of rock samples mineral grain by mineral grain, to deduce much about the thermal histories of rocks and meteorites.

Substitutional order-disorder phenomena are also important in that they play a key role in the energetics and crystal chemistry of numerous solids, including metal alloys, ferroelectric materials, fullerenes, and high-temperature superconductors, as well as rock-forming minerals. Variations in degree of ordering may affect a material's stability, and they can dramatically alter physical properties, including strength, thermal conductivity, electronic properties, and elastic moduli. Thus, pressure-induced ordering has implications for studies in materials science, geophysics, and solid-state physics. In materials science, an understanding of pressure-induced ordering could lead to new techniques for tuning the properties of synthetic materials—ferroelectrics and cuprate superconductors, for example. In geophysics, recognition of high-pressure ordered states in the oxides, silicates, and metal alloys that form much of the Earth's deep interior is essential for developing realistic models of the transport properties and dynamic behavior of our planet. And in solid-state physics, high-pressure order-disorder behavior may provide a sensitive indicator of relative changes in the nature of interatomic potentials.

Detailed studies of the effects of temperature and composition on ordering have been conducted for most rock-forming minerals, as well as for many metal alloys and other synthetic compounds. These investigations are routinely used to estimate maximum temperatures, cooling rates, and chemical environments of igneous and metamorphic

deposits, as well as meteorites. As we attempt to understand the present state and dynamic behavior of our planet, the effects of pressure on order-disorder phenomena are thus receiving closer scrutiny.

Of special interest to earth scientists are iron-magnesium oxides and silicates, which have been studied extensively because of their importance in the crust and mantle of the Earth and other terrestrial planets. Divalent iron and magnesium behave as interchangeable ions in many low-pressure minerals; they have similar atomic radii and both prefer crystal sites having six nearby oxygen atoms. Consequently, iron and magnesium act as largely interchangeable atoms (i.e., in disordered state) in many common crustal minerals, including olivines, spinels, pyroxenes, amphiboles, micas, garnets, and carbonates.

Recent work at the Geophysical Laboratory and elsewhere shows that this situation changes dramatically in many high-pressure minerals, in which iron and magnesium typically separate to occupy distinct crystallographic sites, i.e., toward an ordered rather than random distribution. Examples of iron-magnesium ordering have been recently observed during synthesis of high-pressure phases, including $(Mg,Fe)SiO_3$ orthopyroxene, an important upper mantle phase; $(Mg,Fe)_2SiO_4$ in both the olivine and wadsleyite structures, minerals thought to be abundant in the Earth's upper mantle and transition zone, respectively; and $(Mg,Fe)_{14}Si_5O_{24}$ anhydrous B, one of a large group of phases that may hold water in the mantle. We have also observed ordering of other pairs of metal atoms in high-pressure olivines, garnets, perovskites, and spinels—all mineral structures believed to play important roles in the Earth's deep interior.

Conventional wisdom suggested that at the very high temperatures of the Earth's mantle, most minerals having pairs of similar metal atoms would become disordered, because high temperature tends to favor random distributions of atoms. Indeed, at room pressure feldspars, olivines, pyroxenes, and many other minerals do disorder when subjected to temperatures above 1000°C. But we observe that a number of materials synthesized at high temperature *and* high pressure are far more ordered than expected. A key finding of our studies is that the density of many minerals changes slightly, typically by less than a percent, as a result of ordering. High pressure invariably favors the denser of two competing phases, so pressure provides a driving force for order-disorder reactions that may offset effects of temperature.

In an important advance, we have identified three structural reasons for density changes associated with substitutional ordering. The easiest of the three reasons to rationalize involves ordering of two metal atoms, such as iron and magnesium, between two or more similar sites. Copper-gold alloys illustrate the volume (i.e., density) effects that may accompany ordering of this type. Copper-gold alloy

structures possess a cubic close-packed arrangement of metal atoms, in which every Cu and Au atom is surrounded by twelve neighbors. In disordered Cu and Au alloys, atoms of the two elements are randomly distributed, whereas ordered variants feature the atoms in strictly alternating sites or alternating planes. In every instance, random distributions of larger gold atoms and smaller copper atoms are less efficiently packed, and thus are less dense, than the ordered arrangements. Similar reasoning may be applied to arrangements of iron and magnesium in minerals. In every known case, the ordered variant is slightly denser than the disordered form.

A second, very different situation obtains when aluminum and silicon order in common framework minerals like feldspars and feldspathoids. Although Al and Si atoms differ slightly in size, the densities of framework structures are more closely tied to the magnitude and distribution of angles *between* structural units than to sizes of individual atoms. Depending on the specific nature of the ordered arrangement of Al and Si, density can either increase or decrease with ordering. In the alkali feldspars, for example, aluminum and silicon ordering causes an increase in the density of $NaAlSi_3O_8$, a decrease in the density of $RbAlSi_3O_8$, and no significant change in the density of $KAlSi_3O_8$.

The third and largest ordering-induced density effect, exceeding one percent in some instances, arises in structures where the cations (metal atoms) can adopt different valences (i.e., Fe^{3+} vs. Fe^{2+}) and/or different coordination states (i.e., be surrounded by either four or six oxygen atoms). In the previous two examples, ordering does not drastically change the volume contributions of constituent atoms. Changes in valence or coordination, however, can produce a significant change in the volumes of structural building blocks. An extreme example is provided by $CoFe_2O_4$, which has the spinel structure, in which both iron and cobalt can adopt either 2+ or 3+ valence states, in either 4 or 6 coordination. A disordered variant with trivalent cobalt and divalent iron, for example, is approximately 4 percent denser than an ordered end member with divalent cobalt and trivalent iron. In such instances, pressure is expected to exert a dominant influence on the observed state of ordering.

Studies of pressure-induced ordering have only just begun, and much additional research is needed to document and understand this phenomenon. Three types of studies—high-pressure synthesis, controlled ordering experiments, and comparative compressibility measurements—will enhance our understanding of pressure-induced ordering.

Our understanding of pressure-induced ordering is severely limited by the lack of appropriate samples. While many minerals and synthetic compounds display varying degrees of order, it is difficult to

find two compositionally identical samples having markedly different ordered states. The most basic experiments required to understand pressure-induced ordering, therefore, entail systematic high-pressure synthesis and subsequent characterization of samples displaying varying degrees of ordering.

Of special interest to the mineral physicists would be synthesis at several different pressures (and the same temperature) of samples of ferromagnesian silicates, including the minerals wadsleyite, olivine, anhydrous phase B, and orthopyroxene described above. Multi-anvil devices would be used to prepare samples suitable for study. X-ray analysis, Mössbauer spectroscopy, infrared spectroscopy, and other structural probes of the resulting samples would reveal the extent of cation ordering and the corresponding densities. A suite of compositionally identical samples, which differ only in the pressure of synthesis (and in the degree of Fe-Mg ordering), would thus provide unambiguous evidence for the effect of pressure on order.

Studies of pressure-induced ordering can also provide answers to questions about the rate of order-disorder reactions. We wish to determine how quickly cation distributions equilibrate at high temperature and high pressure, and to discover if it is possible to recover crystals that display states of order characteristic of extreme synthesis conditions. We are especially interested in learning if pressure dramatically affects cation mobility. Increased pressure tends to confine atoms and molecules and restrict their vibrational and rotational motions, so it may be supposed that rates of order-disorder reactions are slower at high pressure.

Given the restricted motion of atoms in a compressed phase, it is possible that high-pressure ordered states may be more readily quenched (returned to room temperature) than those at lower pressure. (Note that quenching protocol in high-pressure experiments is usually to reduce temperature while the sample is at pressure.) If pressure increases ordering, then samples quenched while at higher pressure are more likely to retain their equilibrium-ordered state than those quenched from the same temperature while at lower pressure.

Until accurate in situ measurements of ordering at high pressure and temperature can be made, these effects can be quantified by studying the distribution of iron and magnesium in a mineral such as orthopyroxene, where the state of ordering is a sensitive function of temperature. Several different experimental runs could be carried out at the same high pressure but at different temperatures. In addition, these samples could be quenched at different cooling rates, producing different degrees of order. Documentation of these ordered states could thus be used to determine minimum rates of intracrystalline cation diffusion. A series of such studies at different pressures, furthermore, could place constraints on the effect of pressure on cation diffusion.

Additional insight could be gained if a suite of crystals having varying degrees of order is obtained. Relative compressibilities of these different structural states could be determined by arranging several crystals in the same diamond-anvil-cell mount and probing them by x-ray diffraction. Small differences in compressibility could be detected because all crystals are at the same pressure. These differences in compressibilities could provide a direct measurement of the effects of order-disorder on a mineral's equation of state.

Studies of high-pressure ordering are in their infancy, and we are faced with many more questions than answers about this intriguing and influential phenomenon. In particular, we do not know the extent to which pressure-induced ordering plays a significant role in determining the structure and properties of phases in the Earth's mantle. As we attempt to understand the present state and dynamic behavior of our planet, the effects of pressure on order-disorder reactions deserve closer scrutiny.

Hydrogen: Element of Uncertainty, Element of Surprise

by Russell J. Hemley

Hydrogen is not only the most abundant element in the cosmos, it is also unique. Each atom consists of an electron and a proton, and the two-atom molecule has the strongest of all two-electron bonds. At low temperatures, hydrogen crystallizes as a quantum solid, which means that its nuclei behave as quantum mechanical objects: owing to their light mass, the nuclei are delocalized in accord with the Heisenberg uncertainty principle and must be described by wavefunctions rather than as classical particles like the nuclei of the heavier elements. As such, solid hydrogen is the only quantum molecular solid.

Russell Hemley

With increasing pressure, the interactions between the molecules grow markedly, resulting in a surprising number of new properties. Eventually, at sufficiently high pressure, theory predicts that, despite the strong covalent bond, the hydrogen molecules must break down and form a high-density atomic metal, a dense plasma. This would be a unique state of matter—a quantum metal—and one predicted to have perhaps unusual, if not exotic properties, possibly very-high-temperature superconductivity, for example. At high temperatures, the dense material is believed to be the major constituent of the large gaseous planets, and at still higher temperatures, of stars. It is no

wonder that the laboratory synthesis and characterization of hydrogen in this high-density state has been described as one of the *Key Problems in Physics and Astrophysics*, by the Russian physicist V. L. Ginzburg in his book by that name (Mir Publishers, Moscow, 1978).

The study of hydrogen under high static pressures began with the first loading and observations of hydrogen in a diamond-anvil cell at the Geophysical Laboratory in 1978. Since then, progress here has been extensive, accelerating with a flurry of measurements and breakthroughs in the last several years. Static pressures on hydrogen approaching 300 GPa* have been reached, a greater than twelve-fold compression of the solid at one atmosphere. Equally significant, measurement accuracy, precision, and sensitivity have improved markedly. An excellent example is in the development of new spectroscopic techniques such as synchrotron infrared spectroscopy, which is providing crucial—and often unique—information on the physical and chemical properties of materials at ultrahigh pressures. In addition, there have been major improvements in other optical techniques, such as Raman and Brillouin spectroscopy. Finally, the continued development of synchrotron x-ray techniques has been an unprecedented windfall, making possible experiments on hydrogen that were inconceivable just a few years ago.

On the trail of this exotic quantum metal, a number of new discoveries have been made, most of which were not anticipated by theory. We are learning that hydrogen, from low to high densities, is even more interesting, unusual, and richer in physical phenomena than previously thought.

Tickling Vibrations with Light

In vibrational spectroscopy, radiation is beamed on a material. The photons interact with the target's atoms and molecules, exciting them and producing tell-tale vibrations at characteristic frequencies. The technique has been one of the most useful probes of hydrogen since early in this century.

There are three principal types of vibrational excitations in solid hydrogen: the stretching of molecular bonds (called a vibron), the vibration of the molecules in the lattice (phonon), and the rotations of individual molecules (rotons) (Fig. 1). Measurements of these excitations are particularly important for investigating the high-pressure behavior of hydrogen because the frequencies and intensities of the bands in the spectra reveal essential information on bonding, crystal structure, and degree of orientational (rotational)

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*One gigapascal (GPa) equals ten kilobars, or approximately 10,000 times atmospheric pressure at sea level.

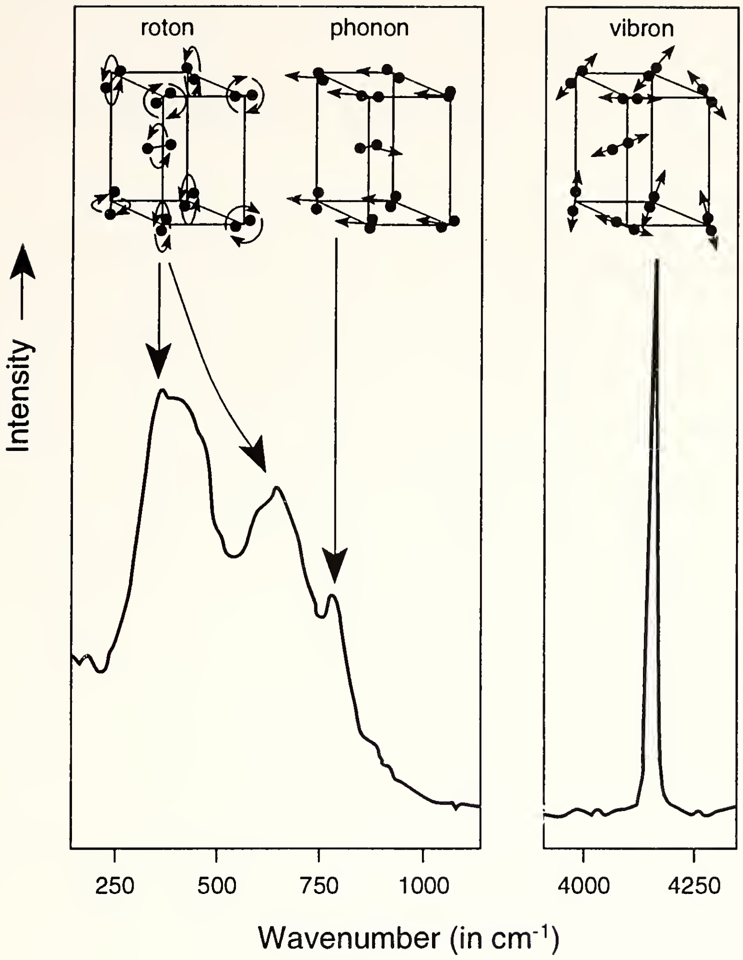

Fig. 1. The principal vibrational excitations of solid H_2 and a representative vibrational Raman spectrum measured at 96 GPa. (Wavenumber in cm^{-1}, the reciprocal of wavelength in cm, is analogous to frequency.)

order. For example, discontinuous and continuous spectral changes as functions of pressure and temperature are indicative of specific types of transitions in the molecular solid. Vibrational measurements can be performed by Raman spectroscopy (a light-scattering technique) and by infrared absorption. In recent years, there have been significant developments in the application of these techniques to high-pressure research in general, and to studies of dense hydrogen in particular, as discussed below.

In the first such measurements of hydrogen at very high pressures, carried out at the Geophysical Laboratory in the early 1980s, for example, the intramolecular stretching mode (vibron) was measured to 60 GPa. The frequency of the vibron mode initially increased with pressure—the expected behavior resulting from increasing repulsion between molecules as they are pushed together. But this trend stopped at 30 GPa, above which the frequency decreased with increasing pressure. This behavior stirred considerable excitement in the field, since a decrease in frequency suggested weakening of the intramolecular bond and increased intermolecular interactions, perhaps in anticipation of an eventual transition to an atomic solid. Subsequently, similar behavior was observed in deuterium, the vibron turnover occurring at about 50 GPa. We sought a deeper and more quantitative understanding of this interesting vibron behavior by studying the infrared spectrum.

Our infrared measurements were possible because of our major advances in techniques with synchrotron radiation, which in turn grew from our interest in another question. In general, the internal vibration

of a molecule in a condensed phase may interact with that of other molecules; in other words, the molecules do not vibrate independently. When this interaction occurs, the vibrational excitation is no longer limited to a single frequency but is dispersed into a range of energies, forming a band. As a result of our interest in understanding this phenomenon in hydrogen, four years ago we were given the opportunity to perform pilot high-pressure experiments and then to develop a new beam line at the National Synchrotron Light Source, Brookhaven National Laboratory, New York. As a feasibility study, the first infrared measurements at pressures in the megabar range were performed, and they were highly successful. We were therefore given the opportunity to develop an unused beam port on the Vacuum Ultraviolet Ring at the synchrotron facility for this new class of experiments. With this new capability, we performed infrared measurements on hydrogen to 180 GPa, well above the 54 GPa of our previous infrared work. These data revealed that interactions between the molecules indeed increase dramatically, much more than expected, as they are brought closer together with pressure. Moreover, the measurements provided an explanation for the decrease in vibron frequency with pressure observed earlier by Raman scattering, and supported the interpretation of bond weakening under high pressure.

Despite the bond weakening, however, the H_2 molecule is still remarkably tenacious under pressure. The molecular vibron is observed by Raman scattering to about 230 GPa, showing that the solid remains molecular to at least this pressure, which is an order of magnitude higher than the transition pressure originally predicted. At higher pressures, the Raman vibron could not be detected. Although the disappearance could indicate molecular dissociation, it could also be caused by the pressure-induced absorption of the exciting laser, by the fluorescence of the diamond and the sample, or by loss of hydrogen to the diamond anvil.

Linus Pauling first showed in the 1930s that certain properties of solid hydrogen arise from the free rotation of molecules in the crystal structure. In other words, the material behaves as if it consists of gas-phase molecules attached to a lattice: the atoms of the molecules refuse to be localized. In our low-frequency Raman studies in the late 1980s, we found that these rotational excitations (rotons) persist to very high pressures (above 150 GPa in hydrogen), showing that the molecules continue to rotate rather freely to very high densities (above tenfold compression). However, in our later work carried out to lower temperatures, we find dramatic changes in the character of the spectra, as discussed below. In addition, our results showed that the frequency of the lattice mode (phonon) measured by Raman scattering for H_2 and D_2 shifts markedly with pressure and suggested that the low-pressure crystal structure persists to above 150 GPa (at room temperature).

A Triad of Phases

In 1988, we performed the first megabar experiments on hydrogen at low temperature (to 77 K). Measurements of the Raman spectrum revealed a major finding. When pressure was raised above 150 GPa at 77 K the original vibron disappeared, replaced by a new vibron 100 cm^{-1} below the old one—signally a phase transition in the molecular solid. The transition was especially intriguing because theoretical calculations about this time were predicting that the molecular solid might become metallic in this pressure range. It thus seemed that the transition could have been an insulator-metal transition, which occurs by closure of the electronic band gap brought about by widening of the electronic bands due to increasing interactions between electrons.

A phase diagram illustrates the pressures and temperatures over which the phases (e.g., gas, liquid, and various solid forms) of a material are stable. The combination of the synchrotron infrared technique and new Raman spectroscopic methods have been used to determine the phase diagram for hydrogen to extreme pressures (Fig. 2). Three phases have been determined in detail: phase I is the high-temperature, low-pressure phase; phase II is a low-temperature high-pressure phase; and phase III is the very-high-pressure phase. The boundary between I and II has a steep slope at low pressure but shows significant curvature with pressure. The I-III line has a steeper slope and extends to temperatures close to room temperatures in both H_2 and D_2. In both isotopes, the three phases meet at a "triple point," a thermodynamic invariant point. The I-II-III triple point for hydrogen, for example, is located at about 120 K and 160 GPa.

During the past year we have studied in detail the phase diagram of the heavier isotope, deuterium (to 200 GPa and from 4 to 300 K). A

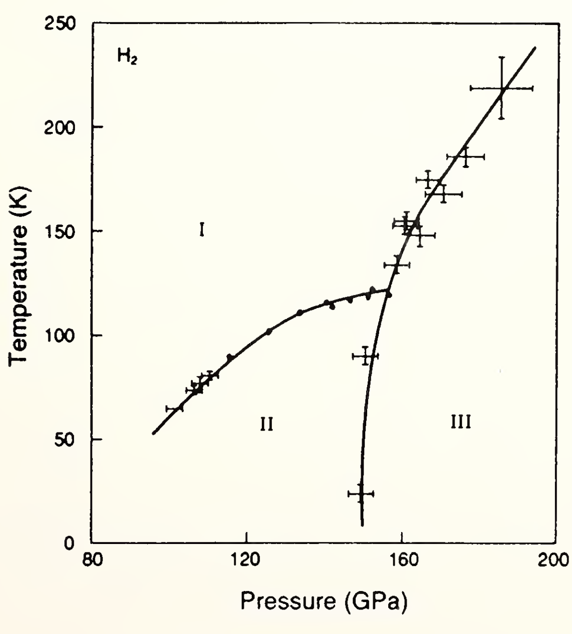

Fig. 2. Experimentally determined phase diagram for hydrogen at megabar pressures.

number of new features have been observed. The I-III phase transition is discontinuous above the I-II-III triple point of deuterium at 167 GPa and 130 K. However, with increasing temperature the discontinuity in the Raman spectrum decreases and eventually disappears. The point at which it disappears is another thermodynamic invariant point, a type of "critical point," which is highly unusual for a solid-solid phase transition. This second invariant point occurs at about 180 GPa and 235 K. Moreover, detailed measurements of the vibron as a function of temperature reveal that deuterium in phase III exhibits features similar to transitions in a very different type of material—liquid crystals. In studying the deuterium transition into phase II, we found unexpected changes in the roton and a huge increase in intensity of vibron sidebands (Fig. 3). These new features signal the formation of a complex crystal structure associated with an unusual quantum mechanical ordering of molecules at low temperatures in phase II. There is now evidence for a second phase transition at these pressures to an intermediate phase with properties of a glass rather than an ordered crystal.

X-ray Diffraction: Breaking the One-Megabar Barrier

As just described, spectroscopy is very useful for identifying phase transitions and for delineating the range of stability of a phase. However, spectroscopy alone cannot establish one of the most crucial physical properties of a solid—its crystal structure. This requires diffraction measurements. In x-ray diffraction, high-energy electromagnetic waves interact with the electrons in the arrays of atoms in a solid and are scattered at specific energies or angles. The measurement of the scattered, or diffracted, radiation provides detailed

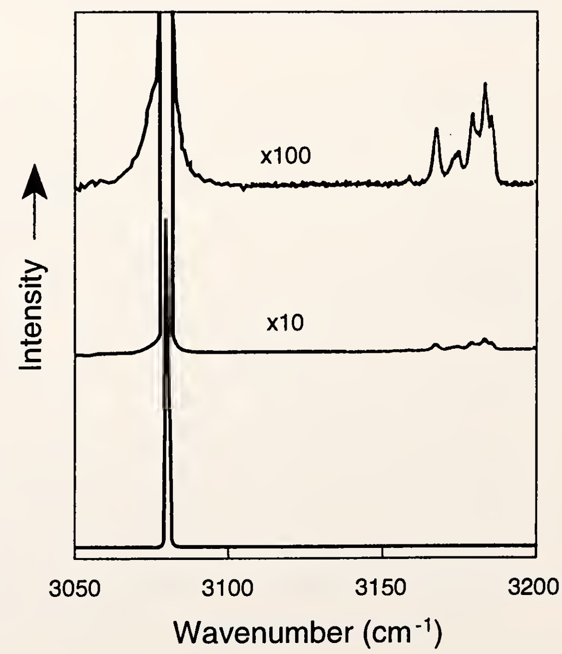

Fig. 3. Raman spectrum of deuterium at moderate pressures and low temperatures in phase II. The intensity of the lower spectrum is expanded by a factor of 10 and 100 in the upper traces. The expanded spectra reveal the newly observed sidebands, a fingerprint of a complex crystal structure of the material in phase II.

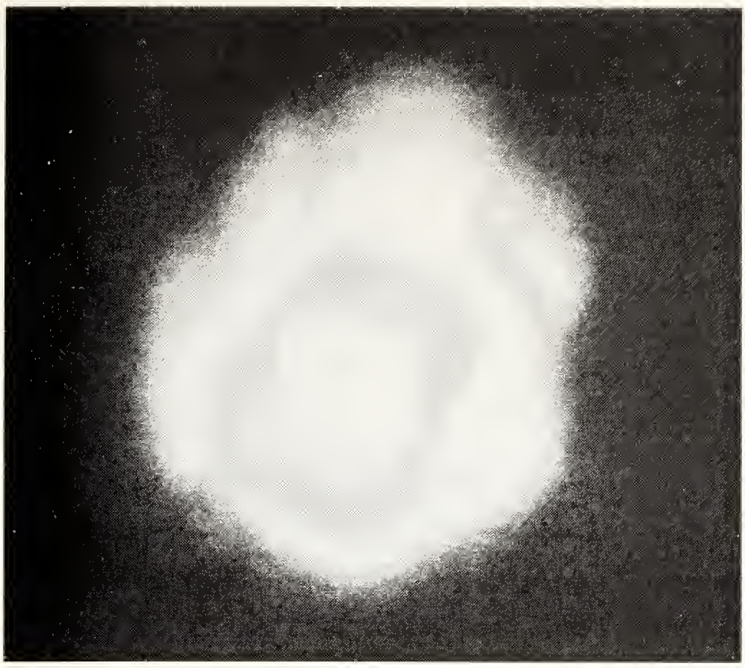

Fig. 4. Photograph of a single crystal of deuterium (in a helium medium) at 105 GPa. This sample was studied by single-crystal x-ray diffraction at the European Synchrotron Radiation Facility (ESRF), Grenoble, France in a collaborative study between groups from Geophysical Laboratory, University of Paris, and the ESRF (Loubeyre *et al.*, to be published).

information on the structure or the arrangement of the atoms in the solid. For many years, it was thought that such structural studies of solid hydrogen at high pressure by x-rays were impossible: the ultralow scattering power of the one electron of the hydrogen atom, combined with the very small size of the samples at high pressure, would conspire to preclude x-ray diffraction and hence direct determination of the crystal structure.

Again synchrotron radiation, this time in the high-energy x-ray region, proved essential. Early work in 1988 demonstrated that x-ray diffraction of solid hydrogen not only is possible but in fact is quite strong if single crystals are studied and highly collimated x-ray radiation from a synchrotron source is used. Techniques were developed to harness and adapt this source to hydrogen experiments, and excellent diffraction data were measured to above 40 GPa. These experiments demonstrated that the hydrogen solid is enormously compressible: at 40 GPa the volume of the solid has been reduced more than sixfold relative to the volume of the frozen solid at atmospheric pressure. The measurements also demonstrated that the crystal structures for both hydrogen and deuterium become increasingly anisotropic with pressure—i.e., the molecules tend to become aligned in a common orientation.

The next phase of this work was to extend the x-ray measurements into the megabar range, where the new phenomena documented by spectroscopy occur. Could measurements be done at one megabar? The problem was difficult because single crystals tend to break down with increasing pressure, generally well before 50 GPa, causing the diffracted signal gradually to disappear into the background. During the past year, we collaborated with two French groups to test use of a high-energy "third-generation" synchrotron source in hydrogen studies. We performed these experiments at the European Synchrotron Radiation Facility at Grenoble (ESRF). In July 1995, we achieved our goal: we nearly doubled the pressure range of the diffraction measurements to record pressures of 119 GPa (295 K). One of the key advances in this effort was the growth of 20–30 mm single crystals of

hydrogen and deuterium within a surrounding medium of solid helium within the diamond-anvil cell. The use of the helium medium acts as a cushion to help preserve the integrity of the crystals to very high pressures (Fig. 4). The measurements demonstrated that the structure remains unchanged throughout the range studied, confirming our earlier spectroscopic data. In addition, although the results were in very good agreement with the earlier x-ray determinations, the material was found to be somewhat more compressible than had been indicated previously.

In the future, we will extend our measurements both to lower temperatures and higher pressures. During the past year, the first x-ray diffraction measurements were carried out on hydrogen at low temperatures (below 100 K) using the ESRF facility. The technique is based on one we developed to study the phase diagram of another quantum solid, helium. Our long-range goal is to study the predicted dissociation transition at higher pressure. Here it will be useful to compare the results of measurements on iodine, which forms a molecular solid at low pressure but becomes a metal at high pressure and thus may be considered an analog of hydrogen. We determined the crystal structure of the dense metallic phase of iodine directly by x-ray diffraction to ultrahigh pressures of 276 GPa. Under these conditions, the material has a beautiful metallic luster with the face-centered cubic structure. For these higher pressure measurements (above 150 GPa), we anticipate using the Advanced Photon Source, with its 7 GeV storage ring, which is this country's third-generation synchrotron source, being built at Argonne National Laboratory.

Symmetry Breaking and Fanfare in the Infrared

The symmetry of an isolated hydrogen molecule prevents direct absorption of infrared light to excite molecular vibrations. A small amount of light absorption is possible for molecules in condensed phases (liquid and solid) as a result of weak interactions of one molecule with its neighbors. This makes possible high-pressure infrared measurements and the evidence for vibrational coupling described on pp. 83–84. It was then startling when in measuring the infrared spectrum of hydrogen in phase III we observed that the intensity of the infrared vibron band increased abruptly by three orders of magnitude (Fig. 5, left). This remarkable result indicated that the transition to phase III involves breaking the symmetry enjoyed by the isolated molecule. But how?

Coming as a surprise to theorists (as was the existence of phase III in the first place), the discovery of the remarkable infrared enhancement of the vibron has led to many theoretical studies. Working in collaboration with Z. Soos of Princeton, we have developed

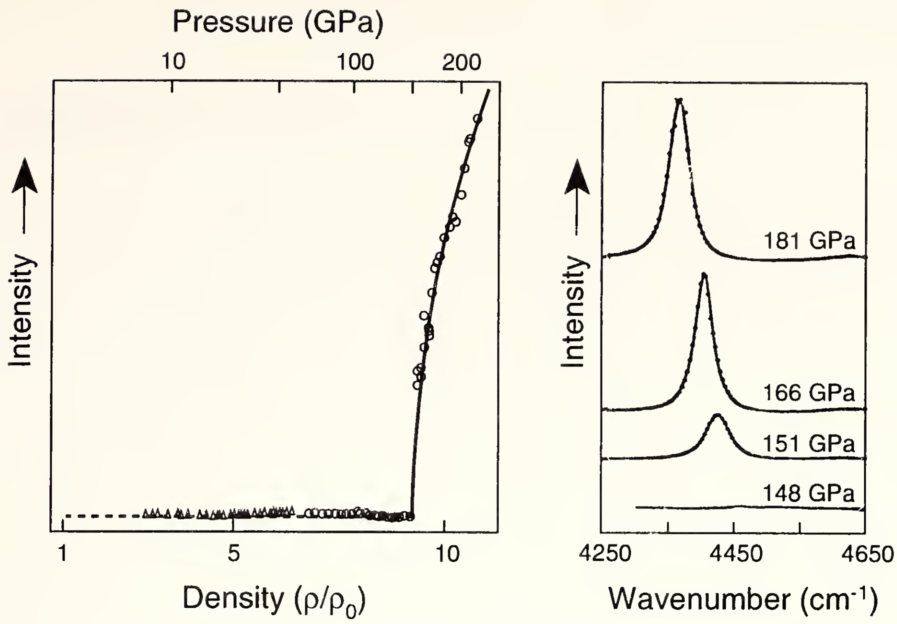

Fig. 5. At left, the intensity of the infrared vibron as a function of pressure (top scale) and density. At right, representative spectra showing the dramatic increase in intensity in phase III.

a model offering that the hydrogen vibron enhancement parallels behavior in charge-transfer salts and conducting polymers upon chemical doping. Our model also predicts the existence of new excited charge-transfer states in the dense solid as the band gap closes. Extending the model, we have developed a theory for the interaction between vibrational and electronic excitations (vibronic coupling) in crystalline hydrogen to explain the observed intensity changes.

We suspected that the enhancement of infrared absorption and frequency shifts of the vibrons (Fig. 5, right) should reflect the same changes, or be manifestations of the same underlying physics. However, the connection between the two could not be explained without new measurements. We therefore carried out careful measurements of the temperature dependence of the infrared activity. The results showed a surprising parallel between the temperature dependence of the infrared absorption and that of the frequency shifts measured by both infrared absorption and Raman scattering. In particular, the infrared intensity change follows the same functional forms as the frequency shift, thereby providing a unified description of these phenomena. In particular, we showed that the two phenomena are related to the "order parameter" concept introduced many years ago by Lev Landau in the theory of phase transitions (Fig. 5, right).

Inside Jupiter

Recent experiments are also telling us something about the outer regions of our solar system. Recently, there has been great interest in the possibility of studying the seismology of Jupiter; in particular, free oscillations of Jupiter have been reported. Since Jupiter is composed largely of hydrogen, the velocity of sound in hydrogen as a function of pressure is crucial for interpreting seismic observations, which until now have been controversial.

The velocity of sound in materials can be measured with a light-scattering technique called Brillouin spectroscopy. In principle similar to Raman spectroscopy, which probes high-frequency vibrations, the Brillouin technique measures low-frequency, or acoustic, vibrations; in practice it is considerably more difficult. We measured sound velocities in fluid and crystalline hydrogen up to 24 GPa using a new Brillouin spectroscopic technique. The results were first used to evaluate the intermolecular interactions in dense hydrogen and to compare with the compressibility determined from the x-ray diffraction experiments. Our analysis demonstrated that the sound velocities in H_2 at conditions of the molecular layer of the Jovian planets are lower than were previously believed. Jovian models adjusted to reflect our results disagree with the reported free-oscillation spectra for the planet by 15%. The effects on Jovian oscillation frequencies of changing interior temperatures, the depth of the predicted transition to the metallic phase, and the fraction of heavier elements within the planet were also investigated. We concluded that major changes either to current models for the planet's interior or to the seismic observations of Jupiter are required to reconcile this discrepancy. Very recently, our measurements have been reproduced by first-principles molecular dynamics simulations.

New High-Pressure Chemistry

There are other applications to the planets. Ground-based and orbiting instruments have provided valuable geophysical observations of gravitational fields and moments that can be used to determine the density distribution within giant planets. Spectroscopic measurements, including those on the recent Galileo probe, reveal information about the surface chemical species of the planets, such as H_2O, CH_4, CO_2, N_2, and NH_3. These materials—gases and ices—interact only very weakly under normal low-pressure conditions (through so-called van der Waals forces or hydrogen bonding). The compositions of the interiors of the large planets are not known in any detail, but they probably contain a significant amount of hydrogen and other light elements. There is little information on chemical interactions and physical behavior of these components under the extreme pressure-temperature conditions of these planetary interiors.

Recent high-pressure studies at the Geophysical Lab have uncovered a rich, new type of chemistry, one that occurs when these simple gases and liquids are mixed under pressure. This was first observed in mixtures of helium and nitrogen, which form the unusual compound $He(N_2)_{11}$ under pressures of approximately 8 GPa. The first example of the new pressure-induced chemistry in hydrogen is its interaction with water under pressure. Under low-pressure conditions,

water molecules form so-called clathrate hydrates, which consist of networks of cages in which guest molecules are contained. They are unstable at moderate pressures as the open networks break down under compression. At higher pressures, it was therefore thought there would be no "mixing" of materials: i.e., the components would separate like oil and water. High-pressure experiments revealed something altogether different. In a high-pressure study of the H_2-H_2O binary system, a novel type of clathrate having 1:1 ratio was discovered. In this high-pressure clathrate, H_2O and H_2 form two interlocking networks, both with the diamond structure. With the efficient packing of molecules afforded by the structure, the new type of clathrate is stable to at least 30 GPa (see Vos, *Year Book 92*, p. 94).

We have subsequently studied several other binary mixtures. The binary system H_2-CH_4 also shows a surprisingly rich high-pressure chemistry. Four new solid compounds were discovered and characterized this year, having H_2:CH_4 molar ratios 1:2, 1:1, 2:1, and 4:1. The crystal structures were determined by single-crystal x-ray diffraction. Interestingly, the 1:1 compound is stable to at least 30 GPa, the maximum pressure studied. Compositions were verified from the bulk compositions of the mixtures, vibrational spectroscopy, as well as x-ray diffraction. Two new solid forms of pure methane were also discovered.

We conclude from this new work that such "gas-ice" compounds may be ubiquitous at high pressures. As basic constituents of the giant planets, these compounds are analogous to the silicate mineral constituents of a terrestrial planet like the Earth.

Onset of Metallization, and More

In principle, the onset of metallization can be detected by the direct measurement of electrical conductivity as a function of pressure, for example, by attaching wires to a sample in the diamond-anvil cell. This type of measurement is possible and indeed has been done, but only at lower pressures where the samples are larger. Such a technique is technically difficult with hydrogen because of the small sample size (e.g., < 20 micrometers above 150 GPa) and also because of pressure-induced reactivity between hydrogen and metals. Spurious reports of metallization of hydrogen have been made in the literature on the basis of attempts to measure conductivity; in each case, the result was later explained as an artifact associated with shorting of the wire leads. The most diagnostic and unequivocal signal of metallization is by the use of optical techniques, measuring the electronic spectrum from short wavelengths (ultraviolet) to the long-wavelength (infrared) range.

Our visible spectra, reported in 1989, showed increasing absorption

from 250 to 300 GPa. This indicated that the electronic band gap was indeed decreasing with pressure, a conclusion supported by subsequent index of refraction measurements. (The presence of a band gap dividing energy bands means that the substance cannot conduct electricity, i.e., is not metallic.) However, from such measurements, we could not determine the onset pressure of metallization. An important consideration is that hydrogen remains transparent to pressures of 230 GPa (i.e., in phase III). However, the visual transparency of phase III does not preclude metallization, since the material could show signs of metallic reflectivity only at infrared wavelengths, and not at visible or ultraviolet wavelengths as with ordinary metals. This is possible if the material is a metal having a small number of conduction electrons, i.e., a semimetal. Thus, band-gap closure could occur well below 250 GPa, as numerous theoretical calculations predicted.

With the new synchrotron infrared technique, we have been able to put new bounds on the onset of possible band-gap closure. Measurements on D_2, for example, indicate that samples remain transparent to 170 GPa at 77 K in the mid-infrared part of the spectrum (to 1200 cm^{-1}). Measurements at higher temperature, however, show increasing absorption,which suggests that there could be important temperature effects on conductivity. This is an active area of study in our laboratory.

Our recent infrared and Raman measurements reveal other new phenomena at megabar pressures. Experiments performed on H_2, D_2, and HD showed unexpected intense new bands. The intensity of the bands increases markedly with increasing pressure at low temperature. These features are particularly intriguing because they appear in the same pressure range as, and exhibit similar temperature dependencies to, a previously observed anomalous low-frequency Raman band, suggesting a common interpretation, but the origin of these new features is not yet understood.

Onward, Theory

The recent discoveries in hydrogen have excited intense study by theorists around the world. The reason is that hydrogen is the starting point for all calculations for atomic, molecular, plasma, and solid-state physics. Although hydrogen has only one electron and proton per atom, its simplicity is deceptive, particularly in the high-density molecular phase. In fact, molecular hydrogen in this regime has been a great challenge for theory. Still, theoretical work on hydrogen has progressed significantly. Such studies are on the cutting edge of condensed-matter theory in general, as accurate calculations for dense molecular hydrogen require techniques that go beyond standard approximations in theoretical physics.

We have actively pursued theoretical work on hydrogen in parallel with our experimental studies, initiating our own series of electronic structure/total energy calculations to aid in understanding new phenomena observed experimentally in dense hydrogen. This work has been carried out in collaboration with R. E. Cohen and I. I. Mazin. These are first-principles calculations in the sense that no parameters from experiments are used. The calculations show that although metallization of hydrogen ought to occur at low pressures by an overlap of valence and conduction bands, the insulating state can persist at specific orientations to pressures above 200 GPa. What happens is that the molecules align themselves in canted structures: not only do these structures preserve the solid as an insulator, they tend to have the lowest energy. Such configurations are consistent with the type of crystal structure identified in the recent Raman scattering experiments.

The Future

The story of Element One under pressure is a story of surprises. With increasing pressure, the solid evolves from a unique quantum molecular state to one characterized by strong intermolecular interactions having parallels to such diverse materials as charge-transfer salts and liquid crystals. There is evidence for new physical phenomena under pressure, including energy localization effects, and new chemistry. The behavior at the higher pressures is not yet clear, but is tantalizing with uncertainties. With recently developed techniques, the prospect is ever nearer for observing the quantum metallic state, the properties of which are not yet established. Synchrotron radiation techniques will be central in this effort.

Recent improvements to our synchrotron infrared system will allow both absorption and reflectivity measurements with infrared light of metallic behavior on ultrasmall samples at the highest pressures. These improvements are essential for tracking the molecular vibron, the signature of the molecular bond, to the highest pressures. Because of the high vibron absorption in phase III, infrared measurements will be a key diagnostic for the breakdown of the molecule to the atomic phases. In addition, the onset of metallization can be determined from the appearance of characteristic absorption and reflectivity at long wavelengths. Moreover, the new synchrotron x-ray facilities now coming on line will permit direct structural studies of the material well into the megabar range.

Perhaps most exciting is the possibility of uncovering still new phenomena in this "simple" yet intriguing material. High-temperature superconductivity has been predicted theoretically for the atomic metallic states, and more recently, for the molecular metallic state of the

material under pressure. During the past year, we have made great progress in the study of the pressure dependence of superconductivity of materials using a highly sensitive magnetic technique developed in collaboration with scientists at the Institute of High Pressure Physics near Moscow. Experiments carried out on $YBa_2Cu_3O_{7-d}$ to 30 GPa have been highly successful, and the prospect of extending such measurements into the megabar range on these and other materials (like hydrogen) remain very good. The recently documented behavior of hydrogen increases the likelihood of truly novel physics at ultrahigh pressures. By analogy to the discovery of superfluidity and superconductivity at extreme temperature conditions, such studies may lead to novel physical phenomena unique to extreme pressures. Meanwhile, these developments continue to demonstrate the power of the pressure variable for deepening our understanding of condensed matter.

Short Reports

Beverly Johnson and Marilyn Fogel: Stable Isotopes in Australian Ratite Eggshell for Paleoenvironmental Reconstructions

The late Quarternary fossil record of ratites (i.e., flightless birds) in Australia is represented by eggshell from the extant species emu (*Dromaius novaehollandiae*) and the extinct species *Genyornis newtoni*. Ratite eggshell is chemically and isotopically well preserved through geologic time, and its stable isotope composition, therefore, has the potential to provide valuable information on paleodiets, and hence paleoenvironments, provided that the isotopic variability in the extant species can be related to modern environments.

Emu eggshells from a nest in the Lake Eyre Basin, central Australia.

Modern emu eggshell samples were collected across a north-south transect of the Australian interior to determine the relationships of stable carbon ($\delta^{13}C$) and nitrogen ($\delta^{15}N$) isotopes of eggshell in a wide range of environments. More-negative values of $\delta^{13}C$ were measured in eggshell found in areas dominated by C_3 plants, more-positive values in areas dominated by C_4 species. The $\delta^{15}N$ of the eggshell was inversely correlated with mean annual precipitation (MAP), where ^{15}N-enriched values were measured in areas of low MAP (<125 mm/year) and ^{15}N-depleted values in areas of higher MAP (>650 mm/year). Based on the modern data, stable isotopes in fossil ratite eggshell from the Lake Eyre Basin, Australia, have the potential to be interpreted as indicators of vegetation and precipitation changes through the late Quaternary.

Thomas Duffy, Chang-Sheng Zha, and Robert Downs: Elasticity and Equation of State of Forsterite to 16 GPa

Comparison of seismic velocities in the Earth with laboratory measurements of acoustic velocities in minerals quantitatively constrains models of the composition and state of the Earth's interior. Forsterite (Mg_2SiO_4) is an important constituent in models of upper mantle composition, and its transition from the alpha to the beta phase is believed to cause the large seismic discontinuity observed near 410-km depth.

Acoustic velocities in single-crystal forsterite were measured at pressures between 3 and 16 GPa using Brillouin scattering in the diamond-anvil cell. From these measurements, the complete set of elastic properties and the aggregate compressional and shear wave velocities were determined. X-ray diffraction was also performed to independently determine the equation of state.

The aggregate compressional and shear velocities in forsterite at the pressure of the 410-km discontinuity were found to be ~3% lower than predicted from earlier, lower-pressure data. By combining our results with existing elasticity data for beta-Mg_2SiO_4, we find that the velocity contrast between the two phases is largely independent of pressure. Our data indicate that the magnitude of the seismically observed velocity jump at 410 km can be satisfied by a mantle containing about 40% olivine by volume. This is significantly below the olivine abundance usually assumed in upper-mantle models.

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Personnel

Research Staff

Francis R. Boyd, Jr.
Ronald E. Cohen
Larry W. Finger
Marilyn L. Fogel
John D. Frantz
P. Edgar Hare
Robert M. Hazen
Russell J. Hemley
Thomas C. Hoering[1]
T. Neil Irvine
Ho-kwang Mao
Bjørn O. Mysen
Charles T. Prewitt, Director
Douglas Rumble III
David Virgo
Hatten S. Yoder, Jr., Director Emeritus

Cecil and Ida Green Senior Fellow

Frank Press[2]

Senior Fellows and Associates

Peter M. Bell, Adjunct Senior Research Scientist
Constance Bertka, National Aeronautics and Space Administration (NASA) and Center for High Pressure Research (CHiPR) Associate
Paula Davidson, Department of Energy (DOE) Associate
Yingwei Fei, Norton Senior Fellow
Glenn A. Goodfriend, Senior Postdoctoral Associate, National Science Foundation (NSF)
Jingzhu Hu, Research Technician (NSF)
Mark D. Kluge, Research Physicist (NSF)
Igor Mazin, NSF and CHiPR Associate[3]
Charles Meade, NSF and CHiPR Associate[4]
Jinfu Shu, Research Technician (CHiPR)[3]
Chang-Sheng Zha, Research Technician (CHiPR)

Postdoctoral Fellows and Postdoctoral Research Associates

Carmen Aguilar, NSF Associate
Guilhem Barruol, NSF Associate and Bourse Lavoisier Fellow, French Ministry of Foreign Affairs[2,5]
David R. Bell, DOE Associate
Brian A. Bergamaschi, McClintock Fellow[6]
Jennifer Blank, Carnegie Fellow[7]
Andrew J. Campbell, Carnegie Fellow[8]
Robert T. Downs, NSF Associate
Thomas A. Duffy, CHiPR Associate[3]
Jon H. Eggert, CHiPR Associate[9]
Reto Gieré, Swiss National Science Fellow[10]
Alexander Goncharov, Carnegie Fellow
Robert P. Ilchik, NSF Associate and Carnegie Fellow[11]
Iris Inbar, Office of Naval Research Associate
Beverly Johnson, Carnegie Fellow[12]
Kathleen Kingma, Grove Carl Gilbert Fellow[2,13]
Victor Kress II, CHiPR Associate[14]
Peter Lazor, CHiPR Associate[15]
Ming Li, CHiPR Associate
Yue Meng, CHiPR Associate[16]
Guoyin Shen, CHiPR Associate[17]
Larry Solheim, Carnegie Fellow[2]
Madduri S. Somayazulu, NSF Associate
Viktor Struzhkin, NSF and CHiPR Associate[18]
John C. VanDecar, Harry Oscar Wood Fellow[2]
Michael J. Walter, CHiPR Associate

Predoctoral Fellows and Predoctoral Research Associates

Pamela G. Conrad, Carnegie Fellow
Julie Kokis, NSF Associate
Fiorella Simoni, NSF Associate[19]
David M. Teter, CHiPR Associate[20]

Research Interns

Mark Acton, Montgomery Blair High School[21]
Aaron Andalman, Montgomery Blair High School[11]
Claude Banta, Bethesda–Chevy Chase High School[11]
Adam Blackman, Bethesda–Chevy Chase High School[22]
Jenny A. Cabrera, Bethesda–Chevy Chase High School[23]
Thomas R. Cooper, George Washington University[24]
Thomas B. Duffy, Jr., Bethesda–Chevy Chase High School[25]
Daniel Feinberg, Haverford College[23]
Jacqualene Harper, Bethesda–Chevy Chase High School[26]
Marc Hudacsko, Montgomery Blair High School[11]
Elizabeth James, Wesleyan University[27]
Eran Karmon, Pomona College[27]
John Kim, Montgomery Blair High School[27]
Billy Lee, Montgomery Blair High School[27]
Rupa V. Patel, George Washington University[28]
Felice Segura, Georgetown Day School[29]
Stacy Shinneman, George Washington University[29]
James W. Shores, University of North Carolina[30]
David Stockman, Montgomery Blair High School[31]
Sujoy Tagore, Montgomery Blair High School[11]
Benjamin Van Mooy, Northwestern University[32]
Joshua Weitz, Princeton University[11]
Emily Yourd, George Washington University

Supporting Staff

John R. Almquist, Library Volunteer
Andrew J. Antoszyk, Shop Foreman
Alessandra Barelli, Research Technician[33]
Maceo T. Bacote, Engineering Apprentice[2]
Bobbie L. Brown, Instrument Maker
Stephen D. Coley, Sr., Instrument Maker
H. Michael Day, Facilities Manager[2]
Roy R. Dingus, Building Engineer[2]
Pablo D. Esparza, Maintenance Technician[2]
David J. George, Electronics Technician
Christos G. Hadidiacos, Electronics Engineer
Shaun J. Hardy, Librarian[2]
Marjorie E. Imlay, Assistant to the Director
Mikie Ishikawa, Library Volunteer
William E. Key, Building Engineer[2]
Lucia Lazorova, Library Volunteer
D. Carol Lynch, Executive Secretary[2]
Paul Meeder, Administrative Assistant
Lawrence B. Patrick, Maintenance Technician[2]
Pedro J. Roa, Maintenance Technician[2]
Roy E. Scalco, Engineering Apprentice[2]
Susan A. Schmidt, Coordinating Secretary
John M. Straub, Business Manager
Mark Wah, Instrument Maker
Merri Wolf, Library Technical Assistant[2]

Visiting Investigators

Nabil Z. Boctor, Washington, D. C.
Alison Brooks, George Washington University

John V. Badding, Pennsylvania State University
Jean Dubessy, Centre de Recherches sur La Geologie des Matieres Premieres Minerales et Energetiques, Vandoeuvre-Les-Nancy, France
Joseph Feldman, Naval Research Laboratory
Donald G. Isaak, University of California, Los Angeles
Deborah Kelley, University of Washington
Allison M. Macfarlane, George Mason University
Kevin Mandernack, Scripps Institution of Oceanography
Charles Meade, National Research Council
Nicolai P. Pokhilenko, Institute of Mineralogy and Petrology, Novosibirsk, Russia
Robert Popp, Texas A&M University
Nicolai V. Sobolev, Director of the Institute of Mineralogy and Petrology, Academy of Sciences, Novosibirsk, Russia
Lars Stixrude, Georgia Institute of Technology
Noreen C. Tuross, Smithsonian Institution
David von Endt, Smithsonian Institution
Willem L. Vos, University of Amsterdam, The Netherlands
Evgeny Wasserman, University of Bristol, England

* * *

[1]Deceased, July 22, 1995
[2]Joint appointment with Department of Terrestrial Magnetism
[3]From July 1, 1994
[4]To March 6, 1995
[5]To August 22, 1994
[6]From March 13 to April 30, 1995
[7]From October 1, 1994
[8]To May 6, 1995
[9]To July 1, 1994
[10]To January 2, 1995
[11]To September 1, 1994
[12]From April 25, 1995
[13]From July 1, 1994 to June 30, 1995
[14]From August 1, 1994
[15]From September 1, 1994
[16]From October 3, 1994 to May 1, 1995
[17]From Septemer 8, 1994
[18]From November 7, 1994
[19]From April 1, 1995
[20]From May 22, 1995
[21]From June 19, 1995
[22]From June 15, 1995
[23]From January 1, 1995 to June 30, 1995
[24]To December 15, 1994
[25]From September 1, 1994 to May 30, 1995
[26]From September 26, 1994 to June 20, 1995
[27]From June 1, 1995
[28]From February 1, 1995 to May 30, 1995
[29]To July 11, 1994
[30]From July 1, 1994 to September 1, 1994
[31]From June 26, 1995
[32]From June 21, 1995
[33]From January 18, 1995

Department of Terrestrial Magnetism

Thin section of a mantle peridotite
xenolith from Hawaii

DTM staff near the main building, Broad Branch Road campus, spring 1995. First row (left to right): Pablo Esparza, Vera Rubin, George Wetherill, Janice Dunlap, Cecily Wolfe, Lawrence Patrick, Lucia Lazorova. Second row: Rosemary Hickey-Vargas, Selwyn Sacks, Rosa Maria Esparza, Shaun Hardy, Sandra Keiser, Fouad Tera, John Almquist, Carol Lynch, Mary Coder, David Rabinowitz, Merri Wolf. Third row: Nelson McWhorter, Bryan Miller, Erik Hauri, Richard Carlson, John VanDecar, David James, Georg Bartels, Alan Linde, Lanbo Liu. Fourth row: Steven Shirey, David Weinrib, Thomas Aldrich, Paul Silver, Louis Brown, Alan Brandon, François Schweizer, John Chambers, Alan Boss. Last row: Conel Alexander, Munir Humayun, Sean Solomon, Michael Day, William Key, Larry Solheim.

Director's Introduction

> To a large extent, American leadership in science has been based on the widespread availability of excellent instrumentation. In an earlier era, scientists could make fundamental discoveries with the equivalent of sealing wax and string. Today an occasional worthwhile observation is made with simple tools, but most significant advances depend on the application of complex instrumentation.
>
> Philip H. Abelson*

Science encompasses the realm of the measurable. As Carnegie trustee and then-president Philip Abelson noted nearly a quarter of a century ago, making the measurements that yield new insight into the workings of the physical and biological worlds increasingly requires access to sophisticated instrumentation. While it is generally acknowledged that carrying out a new kind of measurement, or increasing the sensitivity of a measuring device, or extending one's observations to a new portion of the signal spectrum can lead to a deepening of understanding and even to the discovery of new phenomena, it is also accepted that such advances usually carry costs. The observational, analytical, and computational tools of the modern research laboratory are stunning in their capabilities, but maintaining those facilities at the levels necessary to nurture scientific progress calls for a sustained commitment to the regular development or purchase of new instrumentation. As the diversity and cost of new equipment escalate faster than most institutional budgets, judicious choices must be made among competing needs. The two essays that follow highlight the two largest investments in instrumentation made by DTM over the last several years.

The first, by Paul Silver, summarizes the new findings in

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*Abelson, P. H., The role of scientific instrumentation, *Science 174,* 1081, 1971.

earthquake physics, large-scale tectonics, and earth structure and dynamics that have resulted from the development and deployment of portable broadband seismometers. For decades seismometers and their associated recording systems traditionally operated only within restricted frequency bands, either above or below a prominent peak in the seismic noise spectrum at 0.1–0.2 Hz associated with storm-driven ocean waves. DTM seismologist Selwyn Sacks was one of the first in the field to recognize the scientific value of a broadband seismometer that could operate at high dynamic range over the full spectrum of incoming seismic signals, from large local events and from distant earthquakes alike. His design of an observatory-class broadband seismometer thirty years ago required innovations in both sensor design and data recording technology. Just over ten years ago, American seismologists organized themselves through the Incorporated Research Institutions for Seismology (IRIS) to push for the development of a high-resolution broadband seismometer that would be sufficiently portable for use in field experiments at remote sites, and DTM staff members Sacks and David James were tapped as leaders of the planning efforts. With a substantial investment by the National Science Foundation (NSF) and the efforts of several seismic instrumentation companies, reliable broadband portable seismometers and data recording systems are now commercially available. IRIS maintains about a hundred of these instruments in a national facility that lends them to seismologists for NSF-approved experiments on a first-come, first-served basis.

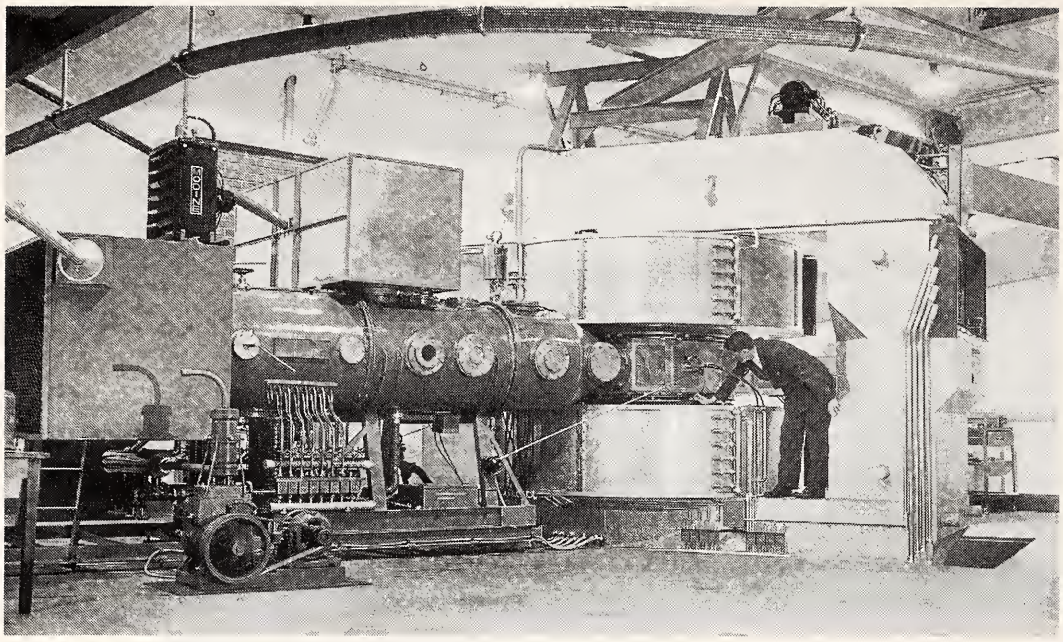
In the early stages of this national program, DTM seismologists realized that the acquisition of our own portable broadband seismometers would give the Department much more flexibility in planning experiments than if we relied entirely on the national facility. This prescient view has served the Department well. As far back as 1989, when DTM led one of the first portable broadband experiments (see *Year Book 91*, pp. 66–78), it was clear that our own instruments could serve as seeds from which large experiments could grow through the addition of other seismometers contributed by collaborators or borrowed from the national instrument pool. Silver's essay, here, provides a more recent example of the value of this leveraging capability. DTM now operates 20 portable broadband stations and is building toward a working total of 25, a number large enough so that several experiments can be conducted simultaneously even if one or two of them employ no instruments from the national facility. This independence has proven critical to our ability to carry out several important experiments in a timely manner, because the national instrument pool is now so oversubscribed that the waiting time for portable broadband seismometers is up to two years. Just as regular access to a large modern telescope is essential to Carnegie's first-class

research effort in observational astronomy, so has the institutional investment in portable broadband seismology yielded an explosion of new types of data that are pushing outward the limits of our understanding of the structure and dynamics of the Earth.

The second essay, by Erik Hauri, describes recent work on inferring the detailed chemical and isotopic composition of the Earth's mantle—and the spatial variations in that composition—from measurements made on rocks solidified from mantle-derived melts. The problem is an important one that bears on the interior dynamics and evolution of our planet, but it is also a difficult one. Magmas erupted at the Earth's surface may differ from their parental melts generated at depth in the mantle because of interactions with the solid material through which the magmas passed to reach the surface. As Hauri points out, it is sometimes possible to circumvent the problem of the interaction between melt and surrounding material in situations where the original melt was frozen and preserved as small, isolated inclusions in mantle samples later carried to the surface by volcanic eruptions. Detailed analysis of these melt inclusions promises to advance significantly our understanding of the mantle melting process and its implications for the origin of chemical heterogeneity in the mantle, but because of the small sizes of the inclusions, such analysis requires ready access to a major new piece of instrumentation, an ion microprobe.

The ion probe is a mass spectrometer which accepts ions ejected from the surface of a solid sample by the sputtering action of an incident ion beam. It is capable of measuring and imaging the chemical and isotopic compositions of solid materials down to spatial scales as small as 1 micrometer with detection limits in the parts-per-billion range. With the assistance of generous grants from the National Science Foundation and the W. M. Keck Foundation, the Institution has purchased a Cameca IMS6f ion microprobe slated for delivery by the end of 1995. The ion probe will make possible a wide variety of new research initiatives at DTM and the Geophysical Laboratory including, in addition to the work on melt inclusions in mantle-derived rock, studies of pre-solar grains in meteorites, mineral inclusions in diamonds from deep beneath ancient continents, and chemical processes at very high pressures. From the outset, the new probe will be operated as a regional facility, with approximately half the operating time reserved for use by scientists from neighboring universities and federal laboratories.

The construction of the laboratory for the new ion probe has posed challenges to rival those involved in marshaling the funds for its purchase. The only existing space large enough to accommodate both the instrument and all associated and anticipated facilities is the subterranean vault that once housed the DTM cyclotron. Built in



Above: The DTM cyclotron in May 1944, shortly after its completion. The 60-inch cyclotron was one of the two largest in operation in the world at that time. Right: Workers removed the 56-ton lower member of the magnet in January 1995.

1940–1943, the cyclotron operated for about fifteen years, primarily to manufacture tracer isotopes for biophysical and medical research. After the cyclotron program wound down in the late 1950s, the vault came to be used principally for long-term storage, although one of the vault's corners provides the best seismic coupling to bedrock anywhere on campus and has been in steady use by the seismology group as a site for seismometer operation and intercalibration for more than thirty years. The largest obstacle to renovation—the dismantling and removal of the more than 200 tons of iron, copper, and steel that had been the cyclotron magnet—was accomplished last December and January. As a result of often-heroic efforts on the part of the Broad Branch Road Engineering Department, under the leadership of Michael Day, the old vault is in the process of being converted into two full floors of laboratory, office, and storage space.

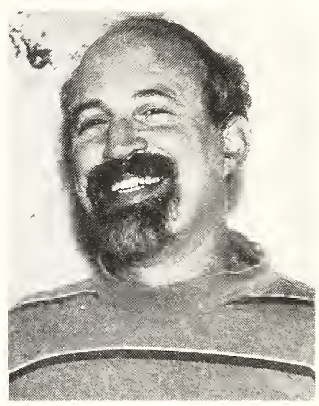
The threads joining the above two tales are common to the history of research at the Carnegie Institution: careful choice of instrumentation made on the basis of scientific priorities and available resources, optimum return on institutional investment achieved by leveraging other assets or by imaginative use of in-house talent, and creative selection of research avenues opened by the new equipment. Certainly Abelson's paean to modern instrumentation is as valid today as 25 years ago, and this institution has a continuing obligation to devote a portion of its expenditures each year to the acquisition and maintenance of critical instrumental capabilities. At the same time, however, the Carnegie tradition of accomplishing as much as possible with the resources at hand has never been more worthy of cultivation.

—Sean C. Solomon

Geophysical Study of the South American Continent

by Paul G. Silver

The Department of Terrestrial Magnetism's seismology effort has been focused in the South American continent for some forty years. When these efforts began, in conjunction with the International Geophysical Year 1957, they involved a concerted effort to detect and map the base of the crust beneath the Andes, using explosions. These beginning studies, in the very early days of explosion seismology, were led by staff member Howard Tatel and director Merle Tuve, and literally involved the whole Department, including George Wetherill and even the Geophysical Lab's Joe Boyd. ("These physicists needed someone who could read a map.")


Paul Silver

The IGY proved the impetus for an entire generation of geophysical and geochemical studies of the Andes by Carnegie scientists. In the mid-1960s Selwyn Sacks installed the world's first broadband, wide-dynamic-range seismographs at three sites in the central Andes. The data from these revolutionary instruments were analyzed to produce three-dimensional maps of the structure of the descending slab and overlying mantle wedge beneath the Andes, with particular emphasis on the distribution of regions of high and low seismic-wave attenuation in the upper mantle. At about the same time, using the broadband instruments in conjunction with the new World Wide Standard Seismological Network, DTM's David James studied surface-wave dispersion to obtain three-dimensional crustal and upper mantle structure beneath the central Andes. That work on Andean structure coincided with the earliest efforts to understand the mountain-building consequences of continental margin subduction zones—the Andes being the primary active example in the world—and led to early, seminal papers on the plate tectonic evolution of the central Andes in terms of the new "mobilist" plate theories. James followed those studies with a comprehensive series of geochemical studies designed to determine the mantle source (slab or overlying mantle wedge?) of the andesitic magmas that comprise the great volcanic edifices of the modern Andes. Continuing work by Sacks and colleagues revealed a number of remarkable new findings, including the discovery that despite the total absence of earthquakes between 300 and 550 km beneath the Andes, the slab is continuous through the Andean region. They also showed that where the slab changes from flat (level) to descending subduction probably reflects differences in the age

and convergence velocity of the descending Nazca plate, zones of flat subduction coinciding with younger, hotter, and thinner oceanic lithosphere. Additionally, they showed that this rapid transition in subduction dip occurs as a contortion, but does not tear the slab, something that had been previously assumed. Later work by postdoctoral fellow John Schneider in the mid-1980s showed that the high-attenuation zone normally found below active volcanic areas is absent in the mantle above the slab everywhere in the zone of flat subduction, thus consistent with the total absence of volcanism in such regions.

Explosion seismic studies by Carnegie and collaborating institutions continued in Peru, Bolivia, and Colombia until about 1976. Through the succeeding years, DTM seismologists have deployed portable instruments in Peru, Bolivia, Chile, and more recently in Venezuela and Brazil.

The enduring appeal of South America, from the earliest studies to the most recent, derives in large measure from the immensity of scale and simplicity of the Andes, the extraordinary level of its earthquake activity, and the seeming primary nature of its mountain-forming processes—the classic textbook example of an ocean-continent zone of convergence. The South American continent on its west side consists of the longest continuous trench in the world, 5000 km, where the Nazca oceanic plate is subducted beneath the South American plate. On this same margin lies one of the world's great mountain ranges, the Andes—a chain that extends the entire north-south length of the continent, and culminates in the 4000-meter-high Altiplano plateau in the central Andes. An object of fascination for centuries, the Andes are a living mountain range, rising even today, as documented by recent geodetic work involving Selwyn Sacks and colleagues. South America is also a continent of contrasts. As if to compensate for the West's hyperactivity, the East is very sedate, having had little tectonic activity for hundreds of millions of years. Its geologic structure is dominated by the Brazilian Craton, an ancient block that has remained remarkably calm since the Precambrian. This dual personality of the South American continent has attracted geophysicists interested in two basic geological problems: the deep structure of ancient stable cratons (that were once, in their time, very active), and the deep structure of the Andes and its relation to the subduction process.

DTM seismologists have recently refocused their attention on the South American continent, armed with a new generation of portable seismic instruments and intent on tackling both of these problems. (DTM's role in developing a national program in portable seismic instruments is described in the director's introduction, pp. 106–107.) Employing its own instruments, DTM has led the way in carrying out experiments in what is called transportable-array seismology, a hybrid

between the short-term (i.e., weeks-long) portable experiments extending 100 km or so, common in explosion seismology, and the permanent global stations that provide on the order of ten years of recording. Such experiments usually span a region about 1000 km long, a scale appropriate for examining the deep structure associated with major geological features like the Andes, and have recording times of 1–2 years. Transportable-array seismology is now one of the fastest growing, most dynamic areas of geophysics. We at DTM not only performed the first such experiment in 1989, a deployment across the western edge of the Canadian Shield, but have recently completed three more in South America and are in the middle of a fourth in Iceland. The experiments in South America have not only led to exciting scientific results, they have also stimulated a renewed interest in that region among the earth science community, resulting in an unprecedented increase of instrumentation.

One of our experiments in South America (by Dave James and former fellow Ray Russo) studied the continent's northern margin, a complex and intriguing plate boundary at the southern edge of the Caribbean. This modest experiment has already shown, through the use of seismic anisotropy, that the geology is a mere surface expression of a deep-seated process extending some 200 km into the mantle. A tomographic image of the mantle, obtained by postdoctoral fellow John VanDecar, has shown that the South American continent actually is overriding and shearing its own slab in this region.

In addition we have deployed two larger-scale experiments, one to explore the Brazilian Craton (BLSP, or Brazilian Lithospheric Seismic Program), the other to study the deep structure of the Andes (BANJO, or Broadband Andean Joint experiment). Both experiments were approximately at the same latitude, and were coordinated so that when they were combined, the resulting network of stations would constitute an east-west transect spanning the entire continent. Indeed VanDecar has already begun using these data to construct an unprecedented tomographic cross-section of the mantle beneath the continent. In the BLSP venture, Dave James in collaboration with Brazilian colleagues deployed ten of our DTM instruments to study the structure of the Brazilian Craton using a variety of seismic techniques. In BANJO the following year, in collaboration with University of Arizona and both Bolivian and Chilean colleagues, DTM (Silver) deployed an east-west seismic line across the latitude where the Andes reached their widest extent. Although only five DTM instruments were used, they formed the core of a much grander endeavor. We were able to borrow a complement of fifteen instruments from IRIS, and in addition we agreed to collaborate with the French Agency ORSTOM, who placed a large number (35) of short-period instruments between our instruments for closer instrument spacing. We also coordinated with a group from

Preparing a portable broadband site in eastern Bolivia as part of the BANJO experiment in November 1994. Left to right: a farmhand helper, Paul Silver, and Randy Kuehnel.

the Lawrence Livermore National Laboratory (G. Zandt), who deployed a 600-km-long north-south line across our east-west line. In addition, we have just recently entered into a similar collaboration with German colleagues at the Free University of Berlin and the GeoForschungsZentrum (Potsdam), who were operating farther to the south. In all, there were eighty stations operating in South America in association with Carnegie's efforts.

Although our instruments have recently been removed and the efforts of both groups to study these questions continue, these experiments were blessed with a significant distraction: three months after the deployment of the BANJO array, and while the BLSP array was still in the ground, the largest deep earthquake ever recorded (magnitude 8.3, 636-km depth) occurred a mere 600 km north of the array. This earthquake was felt as far away as Toronto, Canada. Our data provided an unprecedented glimpse into the event. The cause of such earthquakes, because of their great depth, has baffled seismologists for the six decades since their discovery. At such depth, and at the high temperatures involved, the mantle should flow like putty, not break like glass. Before this earthquake, indeed only six months before, many had thought that an answer had finally been found, as seen in a *Scientific American* article in September 1994. The author proposed a model that was based on faulting associated with a phase transition from olivine to spinel (so-called transformational faulting), which is known to occur in the mantle. But the recent earthquake spoke very clearly, and based on the unique data collected from our experiment, it said "no" to this model.

We have proposed an alternative model, a very simple one, namely that these deep events occur on faults in the descending plate that are originally formed in oceanic lithosphere before subduction, and are

reactivated at depth. We need to explain how they retain the weakness that made them faults at the Earth's surface. One possibility, inspired by previous work of the Geophysical Lab's Charles Meade, is that seawater seeps into the faults before subduction, forming hydrous minerals. Meade showed that even at high pressure, when these phases lose their water, they produce acoustic emissions—i.e., microscopic earthquakes. This mechanism thus could explain the occurrence of deep earthquakes. To test this idea, we are presently looking at the properties of faults in the oceanic lithosphere, and at the properties of hydrous minerals at mantle conditions.

We also used the waves from the 1994 earthquake to study mantle structure. Former postdoctoral fellow Tim Clarke, Dave James, and I examined shear waves bouncing several times off the Earth's core-mantle boundary. They also bounce off known seismic discontinuities in the mantle (the result of changes in the mineralogy of the mantle), allowing us to map the depth of the discontinuities. This depth is primarily a function of mantle temperature (a sort of mantle thermometer), and from these data we have found very cold temperatures near the deep earthquake zone, undoubtedly due to the effect of the cold, descending Nazca plate beneath South America.

Just when we were ready to get back to the work of studying the Andes, and literally hours before we were to drive out to the BANJO stations to remove them, a magnitude-8 earthquake occurred in Chile, just south of our instruments. We again obtained unique records. There have never been such high-quality broadband records so close to such a large earthquake, and we anticipate valuable information both for learning more about earthquakes and for understanding the complex structure of western South America.

The BLSP experiment also received an unexpected but pleasant surprise in the study of mantle structure. Dave James and John VanDecar set out to study the deep structure of the Brazilian Craton, a feature that, based on lower-resolution images, was expected to be associated with high-seismic-velocity mantle, similar to the properties of cratonic regions elsewhere. Yet, when VanDecar and James made a velocity image of the deep mantle, the most outstanding feature was a low-velocity cylinder, some 300 km in diameter, extending throughout the upper mantle. The anomaly lies directly under a zone of ancient volcanism, and they interpret it as a fossil plume conduit associated with the breakup of Gondwanaland where Africa and South America split apart. The important plate tectonic consequence is that the South American plate is moving along with the general mantle convection. It is usually supposed that the motions of the surface plates are decoupled from the mantle below, by a thin asthenospheric layer. Our results, however, showed otherwise.

With their focus on this fascinating continent, DTM scientists have

also begun to consider several long-puzzling questions. For so seemingly simple a continent, South America is full of paradoxes. For starters, even the Andes are a paradox. Why are the Andes there in the first place? And what controls the shape and character of South America, having two basins north and south of the continent, and the large indentation in the center, called the Bolivian orocline, where the magnificent Andes reach their maximum elevation, averaging some 4000 m? In classical plate tectonic theory, mountains are explained as arising from the collision of two continents, like the collision that formed the Alpine-Himalayan chain, spanning from Switzerland to Tibet. Yet, South America did not collide with a continent. The Nazca plate is simply subducting beneath South America along what is called a convergent margin. But convergent margins are found around the Pacific Rim, without associated mountains. Why are the Andes unique?

Ray Russo and I have proposed an answer, based on observations of seismic anisotropy which suggest north-south flow along the South American coastline below the Nazca plate. Our results were recently corroborated by similar observations of anisotropy from the South American portable stations by predoctoral fellow Jascha Polet and colleagues. The key to this model is the rapid westward movement of the South American plate. We suggest that the deep-rooted continent can be viewed as a flat-nosed boat moving against the water, with the subducting Nazca plate acting as a membrane that simply transmits pressure. The water (i.e., the sub-Pacific mantle) is displaced around the sides of the boat (the continent), but it exerts a maximum pressure on the boat where the bow wave forms, at the so-called stagnation point, in the center of the boat. If the boat is not very strong, it will deform in response to this force, buckling in the center, and looking much like the Bolivian orocline on the west coast of South America. The flow around the continent, to the north and south, would then be responsible for the Caribbean and Scotia Basins, to the north and south of South America, respectively (an idea first proposed by Walter Alvarez).

As a way of testing the plausibility of this idea, postdoctoral fellow Larry Solheim set about simulating the process by numerical modeling. Making the properties of the continent and fluid as Earth-like as possible, he moved a deformable continent through a mantle fluid. The mantle fluid directly in front of the continent caused the continent's front end to cave in and deform, most intensely in the center, as expected (Fig. 1). The synthetic Andes reached their peak there, and the resulting shape and deformation look much like South America (at least to a geophysicist!). Thus, the model has passed one of its tests, that of physical plausibility.

If the westward movement of the South American plate can so completely dominate the geology of one side of the continent, then

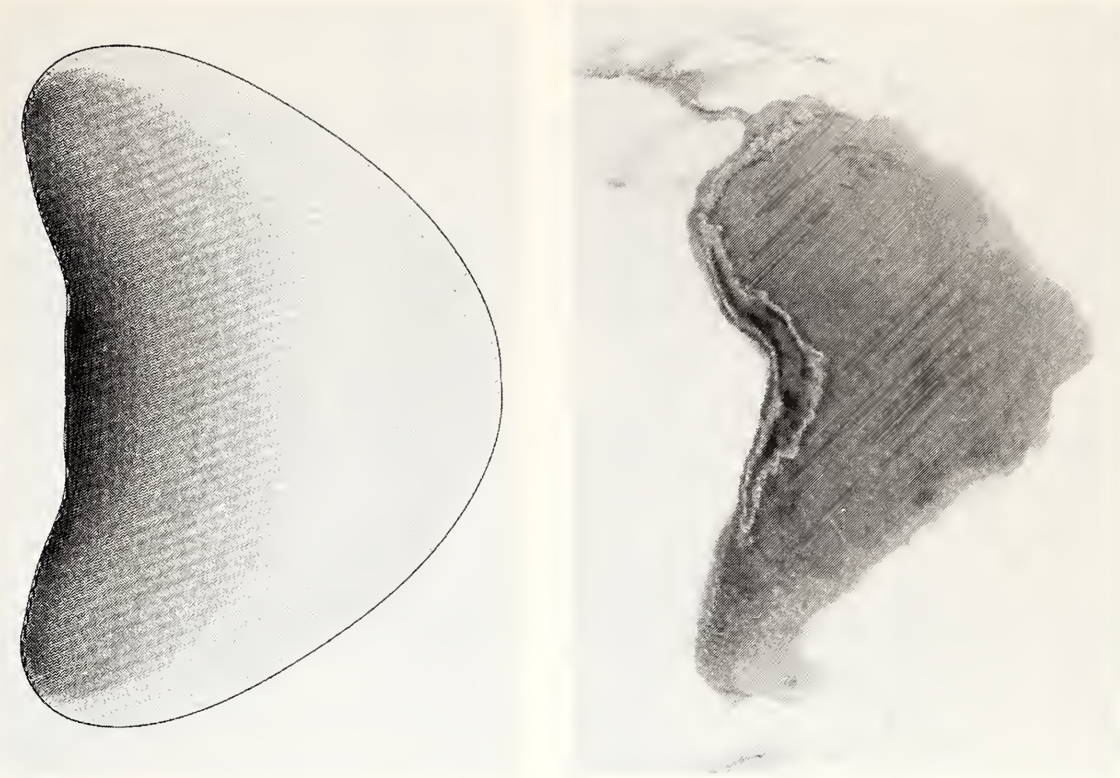


Fig. 1. A numerical experiment by postdoctoral fellow Larry Solheim designed to model the deformation that created the Andes. Left: A triangular-shaped undeformed "South America" is moved to the west through a mantle "fluid." The resistance of this fluid to the motion compresses the western edge of the continent (left), creating the Andes. The elevation ranges from sea level (light shading) on the eastern side of the continent to 2 km (dark shading) on the western edge. The mantle fluid is displaced around the northern and southern tips of the continent, creating a "bow-wave" in the center, serving to maximize the deformation there. Right: A relief map of the South American continent, which highlights the intensity of deformation and "caved-in" shape of the central Andes.

what is the force that is causing this motion? There are not many possibilities. The conventional argument is that the so-called "ridge-push" force drives the plate as the oceanic part of the South American plate moves away from the Atlantic mid-ocean ridge. But this force is too feeble to maintain the lofty central Andes, let alone build the intensely deformed mountains in the first place. The only other possibility is that South America is being literally dragged to the west from below by the general convective currents in the mantle. The work of VanDecar and James, mentioned above, showing that the upper mantle is moving along with South America (as well as earlier work by Sacks on the deep structure of the South American lithosphere), provides further support for this conclusion.

We have described here studies that carry on the observational tradition of DTM seismology on the South American continent. We have also presented hypotheses as to the basic processes that may have played a major role in the evolution of the South American continent. These are testable hypotheses, and we at DTM are fortunate to possess the tools to perform the necessary experiments.

Acknowledgment: DTM's Randy Kuehnel has directed the field operations of all five of our transportable array experiments. His untiring efforts are for the most part responsible for their success.

Migration of Magma from the Convecting Mantle

by Erik H. Hauri

The theory of plate tectonics has served well the scientific pursuit of increased understanding of the planet beneath our feet. Plate tectonics provides a mechanism which can explain many features of the history of the Earth's surface, including continental drift, mountain building, earthquakes at plate boundaries, violent volcanism around the Pacific Ocean, and the more gentle underwater eruptions that build the mid-ocean ridges. The separation of the Earth's surface into distinct mobile plates provides a single elegant mechanism to explain these phenomena, which were once thought to be completely independent of each other.

Erik Hauri

Many volcanic oceanic islands, however, are clearly "nonconformists" in the plate tectonic paradigm, and defy explanation within its context. There are several cases where a group of oceanic islands, such as the Hawaiian Islands, form a linear chain located within the interior region of a plate, far from its seismically and volcanically active boundaries. Plate tectonics fails to explain adequately these cases. The Earth's surface does indeed consist of plates, but most of the mass of the Earth lies beneath these plates, and it is to this deeper region that we must look to understand the formation of these linear island chains.

The motions of the mantle differ considerably from the motions of the plates at the Earth's surface. Beneath the continents, the mantle is quite ancient, cold, and buoyant (see Carlson *et al., Year Book 93*, pp. 109–117), and as a result, it forms a deep "keel" which travels with the continent as the continental plate drifts. The mantle beneath the thinner oceanic plates, however, is in a constant state of motion, as a result of convection currents driven by heat flowing from the Earth's deeper interior and cooling of the plates at the Earth's surface. This mantle convection drives a subsurface flow which may be much more rapid than the gentle drifting of the plates over the Earth's surface. Since the continental plates are so thick and buoyant, they are not generally mixed into the Earth's interior by these convective motions (and thus they retain their old age), but most of the oceanic plates are returned to the deeper Earth by subduction, and are mixed back into the mantle to varying degrees. An important component of mantle circulation is in the form of hot upwelling currents which can create substantial volcanism at places within the plate, such as Hawaii (Fig. 1). These hot

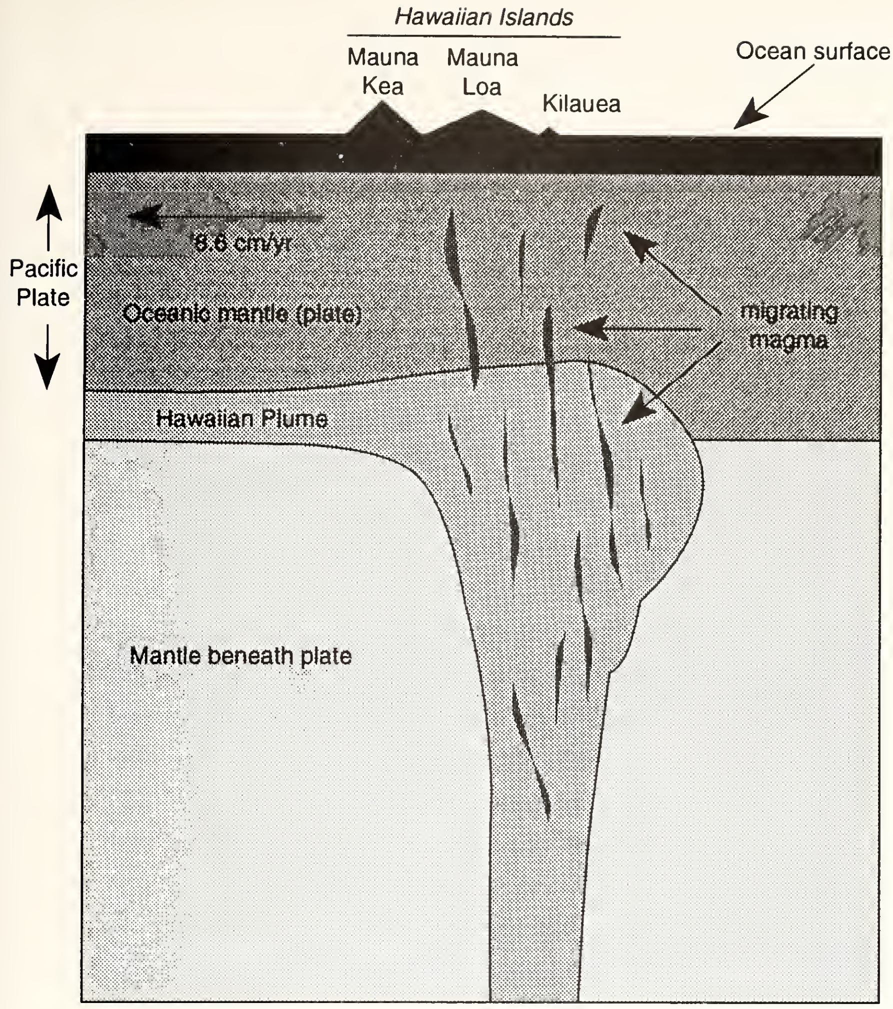


Fig. 1. Schematic drawing of the mantle flow beneath the Hawaiian Islands. The Hawaiian plume rises up through the mantle, incorporating mantle material from different depths, and is deflected laterally by the drifting Pacific plate. Magma generated within the plume migrates through the plate, and is eventually erupted to form volcanoes such as Mauna Kea, Mauna Loa, and Kilauea. Migrating magma may react with the Pacific plate during ascent.

upwelling currents are known as mantle plumes, and they can contain mantle material from many different depth levels.

Sampling the Earth's Deep Interior

Because the convecting mantle below the plates is largely inaccessible to direct sampling, the chemical identity and history of this region of the Earth is often inferred from the chemistry of mantle-derived lavas that have erupted at the Earth's surface, now in the form of volcanic rocks called basalts. Unlike volcanic rocks erupted at the boundaries of tectonic plates, lavas at Hawaii (and many other ocean islands) penetrate and are erupted at surface locations well inside the plate boundaries. The Hawaiian Islands were created as the Pacific plate drifted like a conveyor belt over a hot stationary upwelling beneath the plate, known as the Hawaiian mantle plume (Fig. 1).

The chemical and isotopic compositions of basalts from ocean islands such as Hawaii are quite different from those erupted at mid-ocean ridges, where the plates are spreading apart. Because of the distinct chemistry of the basalts derived from the Hawaiian plume, we may be able to infer two important aspects about the composition of the mantle coming up in this plume. First, the part of the Earth's interior that is feeding this plume must be compositionally distinct from the upper levels of the mantle where mid-ocean ridge magmas originate. Second, these two regions of the mantle must have remained isolated from each other for a long period of time, perhaps as long as a billion

years, despite the convection which seemingly would have tended to mix them together.

The ability to make such inferences from the chemistry of erupted lavas has led to many interesting conclusions about the degree of chemical variability in the Earth's mantle. Isotope ratios measured in oceanic lavas are commonly used to identify and classify different mantle reservoirs within the Earth's interior. Determination of the isotope ratios of many different elements can delineate a unique "fingerprint," or "isotopic signature," which identifies a lava's source reservoir. Studies of many hundreds of oceanic lavas over the last twenty years have identified five primary reservoirs within the Earth (Fig. 2). One of the major goals of mantle geochemistry is to determine the locations, ages, and individual histories of these reservoirs. For example, one of the identified mantle reservoirs (labeled FOZO in Fig. 2) is common to many of the oceanic lavas erupted above mantle plumes (for example, the Society Islands), and it is likely that this widespread reservoir is the lower mantle below 670 km depth. In addition, several of the most extreme compositions (labeled EM1, EM2, HIMU) are thought to be the chemical expressions of near-surface material (such as ocean crust and sediments) which had been returned to the deep interior of the Earth along with subducting plates (see Morris, *Year Book 88*, pp. 111–118), and which is now being carried up in mantle plumes such as the one beneath Hawaii (Hofmann and White, *Year Book 79*, pp. 477–483).

We must keep in mind, however, that the lavas, being partial melts of the mantle, are indirect samples of the Earth's interior. The ability to

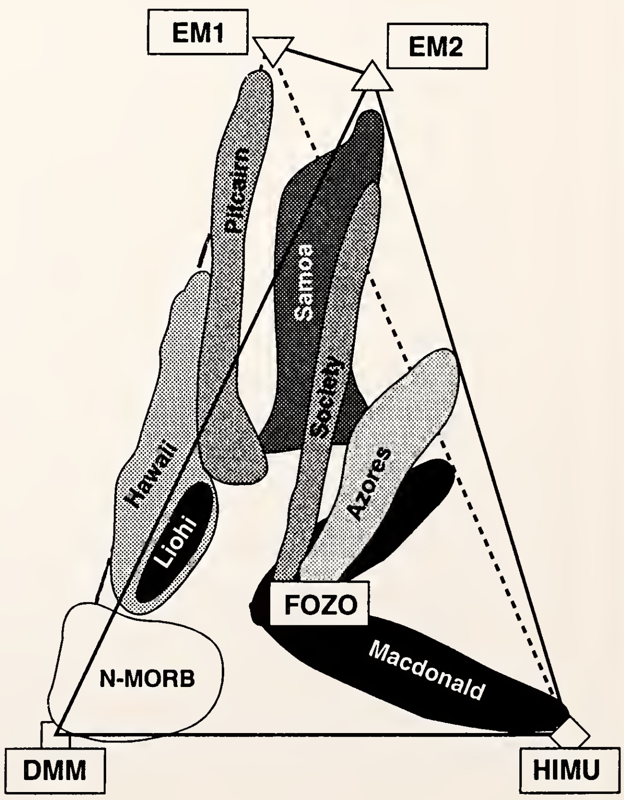


Fig. 2. Projection of 3-d plot of Sr, Nd, and Pb isotope ratios for lavas from oceanic islands, i.e., intraplate hotspots. The data are completely enclosed by a tetrahedron, the corners of which are the extremes of the data. The lavas erupted at individual islands or island chains are indicated by elongated fields (e.g. Hawaii, Samoa, Azores). The extremes of the data are labeled and correspond to identified mantle reservoirs within the Earth's interior: the upper mantle (DMM) and materials returned into the mantle with the oceanic plates during subduction (EM1, EM2, HIMU). The lower mantle reservoir (FOZO) plots inside the tetrahedron, and consists of material incorporated into rising mantle plumes. N-MORB is normal mid-ocean ridge basalt.

make inferences about the mantle from erupted lavas depends critically on the quality of the "chemical connection" between mantle source regions and the magmas derived from these regions.

New research in geochemistry at DTM seeks to determine the validity of this chemical connection by studying the coupled physics and chemistry of melting and melt transport. Because isotope ratios are unaffected by magma generation processes, it has been commonly assumed that the isotopic compositions of different regions of the Earth's mantle correspond directly to isotope ratios measured in lavas derived from these regions. The magma transport process from source region to the surface has usually been assumed to have no effect on isotope ratios. However, new insights from the fluid mechanics of magma transport suggest a very different possibility. Transport of magma from the site of melting can alter the isotopic composition of the magma if it reacts with another region of the mantle along its path to the surface (Fig. 1). Since ocean ridge magmas are erupted at plate boundaries where the plates are spreading apart, these magmas can escape directly from the mantle with isotope ratios unaltered. Mantle plume magmas, however, must penetrate the overlying plate before they erupt, and the plate may be very thick (80–90 km thick beneath Hawaii, of which ~70 km is mantle). Since the likelihood of magma-mantle reaction within the plate may be high, our goal is to determine how important the transport process is in modifying the compositions of migrating magmas.

Magma Reaction Features in Oceanic Mantle Xenoliths

One way to examine the extent of magma reaction during melt transport is to examine fragments of the oceanic plate which are occasionally contained as xenoliths in erupted lavas. Oceanic mantle xenoliths are quite different from their ancient (>2–3 billion year old) counterparts found on the continents (see Carlson *et al.*, *Year Book 93*, pp. 109–117). The oceanic xenoliths are quite young, having been removed either directly from the underlying mantle plume during recent volcanism, or from the plate, which itself typically has an age of less than 150 million years. Thus the chemical information they contain is relevant to very recent processes in the history of the volcanoes in which they occur (Fig. 3).

The large majority (>90%) of oceanic mantle xenoliths examined to date have experienced some degree of reaction with magmas in the mantle. This is indicated by the presence of pockets of melt and gas as tiny inclusions within the xenolith minerals, by new crystals which precipitated from reacting melts, and by the general enrichment of trace elements known as "incompatible elements," which have high concentrations in magmas and are thus sensitive tracers of

Fig. 3. A fragment of a lava flow from Hawaii containing oceanic mantle xenoliths. The fine-grained gray basalt encloses the coarse-grained xenoliths. These xenoliths are fragments of the Pacific plate which were incorporated into the lava during its ascent. They record reaction of magma with the mantle parts of the plate during magma transport. The chisel is 6 inches long.

magma-mantle reaction. From the study of these oceanic xenoliths, there can be little doubt that magmas do react with the mantle part of the plate during transport to the surface. While it is understood that the mantle part of the plate changes its composition during this reaction, the studies cannot tell us if the process significantly changes the composition of the magma itself. Because the xenoliths are broken, isolated fragments which only occasionally make it to the surface, we cannot estimate the amount of the plate which has reacted with the magma unless we also examine the magma chemistry.

Isotope Signatures in Erupted Lavas: Simple or Complex Origins?

Magma-mantle reaction features like those observed in xenoliths derived from the oceanic plates can create a very complex isotopic signature in erupted lavas, which may have little correspondence to the original isotopic signature of the mantle plume (Fig. 4). If plume magmas react with a large volume of the plate during ascent, their isotope ratios may be drastically changed. Multiple mantle sources might be inferred where none exist (see question marks in Figs. 4 and 5), and the isotope signatures of mantle source regions estimated from the lavas may be very different from those actually present in the mantle. It is thus crucial to determine if magma isotope signatures are altered during melt transport. If such alteration is considerable, then many of the inferences about mantle compositions made from derivative lavas (see Fig. 2) may be grossly erroneous.

The coupled physics and chemistry of the transport process can be described in the following way. Magma forms as a partial melt of the mantle; the percentage of a mantle source region that consists of melt is known as the region's porosity. During the initial stages of magma migration, magma separates from the source region and moves toward the surface by porous flow at a velocity which depends on the porosity in the surrounding mantle, whether in the plate or below.

Magma-mantle reaction during melt migration will cause different elements to be transported at different fractions of the magma velocity, because some elements spend more time reacting with the mantle than other elements. The transport velocity of an element is given by the following simplified equation:

$$W_{element} = \frac{W_{melt}}{1 + K/\phi},$$

where $W_{element}$ is the element transport velocity, W_{melt} is the melt velocity, ϕ is the porosity, and K is a measure of the "reaction time" of different elements. The elements with low reaction times (small K) travel at velocities close to the melt velocity; other elements with longer reaction times lag behind and are thus separated from the other elements, much like elements in a chromatographic column. If the porosity is low (small ϕ), small differences in reaction times are magnified and elements may travel at very different rates, so this "chromatographic" element separation may be large. The process is analogous to guests traveling to a party by subway train (the guests are the isotopes, the train is the moving magma). Everyone gets to the subway station at the same time, but those who know their way through the station get right on the train and arrive at the party first, and those who spend time wandering around in the station arrive late. If the corridors in the station are short, wide, and straight, the wandering guests will not be far behind, but if the corridors are long, narrow, and winding, they will arrive very late.

Prior to our improved understanding of the fluid mechanics of magma migration, this process was assumed to be unimportant for

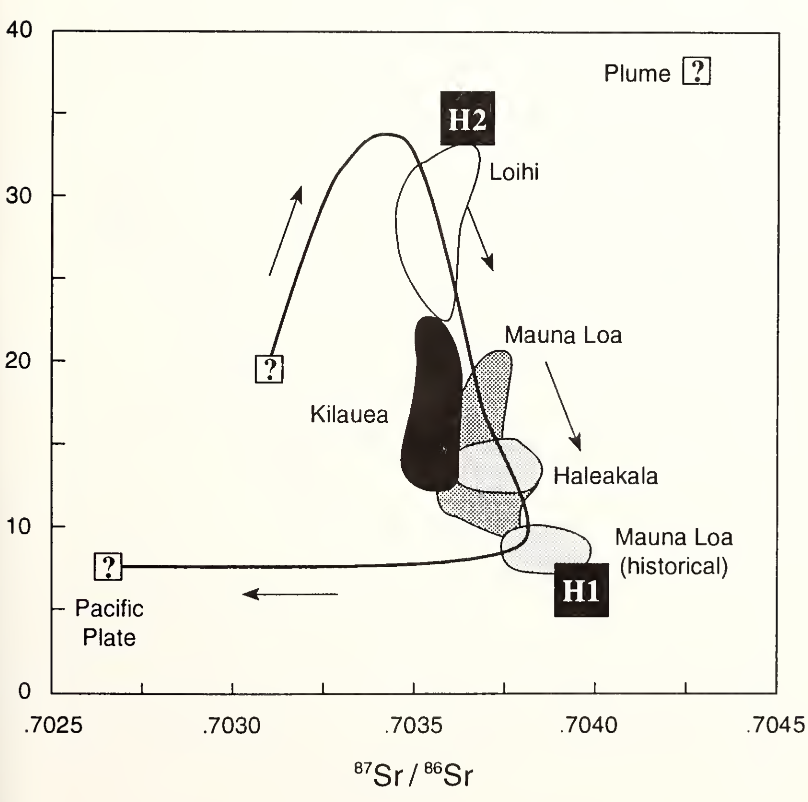


Fig. 4. Helium (He) and strontium (Sr) isotope data for lavas from Hawaii are shown as fields identified by the names of individual volcanoes (Mauna Loa, Kilauea). These lavas are thought to originate by the mixing of two distinct sources within the Hawaiian mantle plume, estimated to lie at the extremes of the data (boxes H1 and H2) assuming that melt transport does not affect isotope ratios in erupted lavas. Melt reaction processes, however, could create the same array from very different mantle source compositions (for example, question marks and solid curve). This possibility may complicate the estimation of mantle source ratios from simple extrapolation of data arrays such as those shown.

mantle plume magmas because the differences in elemental reaction times are subtle for the isotopic tracers most commonly used, such as the isotopes of strontium (Sr) and helium (He). However, melt migration experiments have recently demonstrated that magma can be transported by porous flow at extremely low porosities (down to about 0.1%), which can accentuate even subtle differences in reaction times and produce confusing results such as those shown in Figure 4. Applying the earlier analogy, porous flow "corridors" in the plate are indeed narrow and winding. But are they long enough to achieve the elemental separation expected from the fluid mechanics of melt transport?

The length scales over which magma reacts during porous flow can only be constrained by measuring the isotopes of an element having a very different reaction time than the other isotope tracers. Osmium (Os) is such an element, and it is unique among the isotope tracers in this regard. Because Os is present at very low concentrations in magmas, Os isotopes in the magma are very sensitive to small amounts of reaction with the surrounding mantle. However, it is only recently that we have gained the ability to measure Os isotopes at the low concentrations and with the stringent precision required to examine this process in sufficient detail (see Shirey and Carlson, *Year Book 90*, pp. 58–71).

In collaboration with Mark Kurz (Woods Hole), Mike Garcia (University of Hawaii), Fred Frey (MIT), Mike Rhodes (University of Massachusetts), Don DePaolo (Berkeley), and Ed Stolper (Caltech), we have begun a systematic Os isotope study of time sequences of lavas from several Hawaiian volcanoes. Hawaiian volcanoes are particularly well suited for this investigation, since we can examine distinct stages

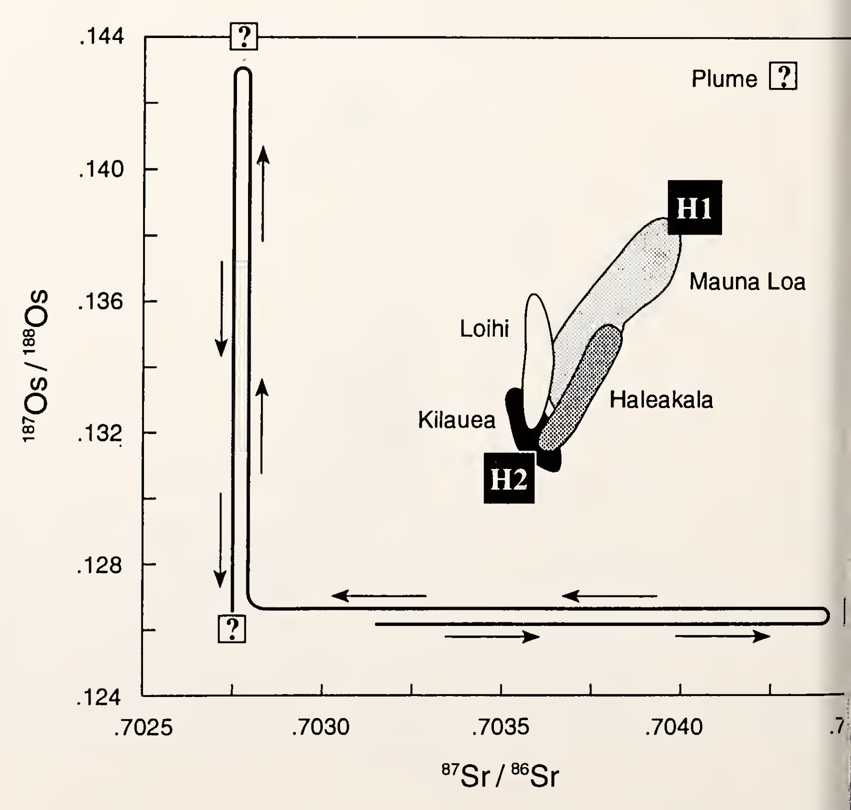


Fig. 5. Osmium (Os) and strontium (Sr) isotope ratios for Hawaiian lavas; fields and symbols, as in Fig. 4. Melt reaction during magma transport would produce extreme decoupling of Os isotopes from Sr isotopes, producing the solid line with arrows. This process is clearly incapable of reproducing the good correlation between these isotope systems seen at Hawaii. The data thus support the idea that mantle sources within the Hawaiian plume can be represented by the extremes of the data array for Hawaiian lavas (black squares H1 and H2), rather than more-complicated possibilities which would have a complex relationship to the lava isotope signatures (question marks).

of volcano evolution which are characterized by different eruption rates, and determine where magma-plate reaction might have had an important effect on magma chemistry.

The test is straightforward: if elements with subtle differences in reaction times are separated, then Os will be very strongly separated, or "decoupled," showing no correlations between Os and other isotopes (such as Sr). The new data from Hawaii, however, show very good correlations between Os and Sr isotopes (Fig. 5). There is only one way that this correlation can have been produced. The porous flow corridors in the plate must be so short that little elemental separation takes place during magma migration, even at low porosity. Magmas in the plate migrate by porous flow only for short distances, perhaps only a few hundred meters. After this, the magma segregates into channels and is on a fast path to the surface, to be erupted without further chemical reaction. With reference to the subway analogy, the corridors are narrow and winding, but they are so short that no one gets lost, and all the guests get on the train at about the same time. It is perhaps only at the very last stages of volcanism, when eruption rates decline sharply and mantle xenoliths begin to appear in erupted lavas, that magma-mantle reaction within the plate strongly affects magma chemistry.

Our conclusion is that the isotopic ratios of the vast majority of ocean island magmas are not hopelessly altered during transport through the oceanic plates from deep within the Earth. These lavas faithfully represent their mantle source regions, and accurately convey the full spectrum of chemical variability within the convecting mantle.

Our future work on magma generation will focus on understanding the actual melting process itself, in an attempt to get one step closer to the actual compositions of mantle plumes. We know that melting begins in small, isolated pockets within plumes. Erupted lavas represent billions upon billions of these melt pockets formed over a range of depths, which are mixed when individual melt channels merge at higher levels above the mantle plume. Since erupted basalts can tell us about processes occurring in the plate above the plume, in order to study processes closer to the plume, we need to examine the individual melt pockets before they are mixed. Fortunately, these initial melts are often preserved as small inclusions, which are enclosed within minerals in the basalt (Fig. 6). In addition, these melt inclusions trap volatile components like water, carbon dioxide, sulfur, and chlorine, which escape from lavas erupted at the surface. The concentrations and isotopic compositions of these compounds can be key indicators of recycled components in the convecting mantle.

Because of their tiny size, often less than 50 micrometers in diameter, the only way we can study the trace element and isotope geochemistry of individual inclusions is with an ion microprobe.

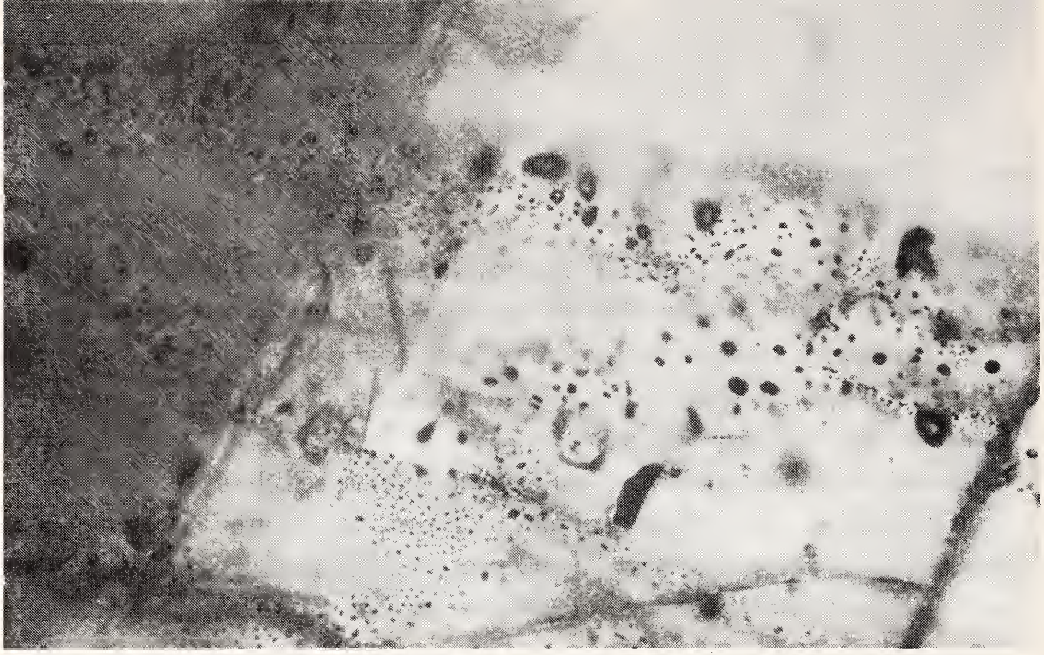


Fig. 6. Melt, fluid, and vapor inclusions are shown as tiny bubbles trapped within olivine crystals in an oceanic mantle xenolith from Hawaii. The field of view is about 1 mm across. These trapped components represent relatively pure melts derived from the mantle beneath Hawaii; because they were isolated within crystals, they were preserved from mixing and reaction. Future research at the new DTM ion microprobe facility will focus on the origins of these inclusions and the processes of melting within mantle plumes.

Research on melt inclusions will be a primary focus of the new DTM ion microprobe laboratory, scheduled to open in 1996. The ion microprobe is an instrument which is uniquely able to examine trace element and isotope geochemistry at very small scales, and on the smallest of geological specimens. The capabilities of this instrument will allow us to examine the tiny, but nevertheless accessible, products of melting occurring within the otherwise inaccessible parts of the convecting mantle.

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Personnel

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Alan P. Boss
Louis Brown, Emeritus
Richard W. Carlson
John A. Graham[2]
Erik H. Hauri
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Sean C. Solomon, Director
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George W. Wetherill

Members of the Broad Branch Road Engineering Department, clockwise from top left: Roy Scalco, William Key, Michael Day, Maceo Bacote, and Roy Dingus.

Senior Research Fellow

Frank Press, Cecil and Ida Green Senior Fellow[3]

Postdoctoral Fellows and Associates

Guilhem Barruol, NSF Associate and Bourse Lavoisier Fellow, French Ministry of Foreign Affairs[3,4]
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Harold M. Butner, NASA Associate
John E. Chambers, NASA Associate[6]
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Munir Humayun, Carnegie Fellow[7]
Tsuyoshi Ishikawa, Carnegie Fellow[8]
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Bryan W. Miller, NASA Associate[11,12]
Elizabeth A. Myhill, Carnegie Fellow[13]
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Cecily J. Wolfe, NASA Associate

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Nguyen Hoang, University of Illinois, Chicago
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Shaosung Huang, Virginia Polytechnic Institute and State University
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Noriyuki Namiki, Massachusetts Institute of Technology
Frédéric Nègre, University of Paris VI
Jasha Polet, California Institute of Technology
Mark Simons, Massachusetts Institute of Technology
Hong Kie Thio, California Institute of Technology

Research Interns

Katherine Bierlein, National Cathedral School, D.C.[16]
Arun Vemury, Montgomery Blair High School, Maryland[17]
Steven C. Schoenecker, Princeton University[18]

Supporting Staff

Michael J. Acierno, Computer Systems Manager
John R. Almquist, Library Volunteer
Maceo T. Bacote, Engineering Apprentice[3]
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Mary McDermott Coder, Editorial Assistant
H. Michael Day, Facilities Manager[3]
Roy R. Dingus, Building Engineer[3]
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Rosa Maria Esparza, Clerk-Receptionist
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Visiting Investigators

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Craig R. Bina, Northwestern University
Jean Carignan, Université de Montréal, Canada
Inés Lucía Cifuentes, Carnegie Institution of Washington
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Nathalie J. Valette-Silver, National Oceanographic and Atmospheric Administration
Elisabeth Widom, National Institute of Standards and Technology
David R. Williams, National Space Science Data Center

* * *

[1]From September 19, 1994
[2]Holds additional appointment as Adjunct Staff Member, The Observatories of the Carnegie Institution
[3]Joint appointment with the Geophysical Laboratory
[4]To August 22, 1994
[5]From November 1, 1994
[6]From October 10, 1994
[7]From August 8, 1994
[8]To September 15, 1994
[9]To June 30, 1995
[10]From June 1, 1995
[11]From October 4, 1994
[12]Joint appointment with the Space Telescope Science Institute, Baltimore
[13]To December 31, 1994
[14]To November 30, 1994
[15]From June 24, 1995
[16]From June 12, 1995
[17]From June 19, 1995
[18]To August 31, 1994
[19]To September 30, 1994

The Observatories

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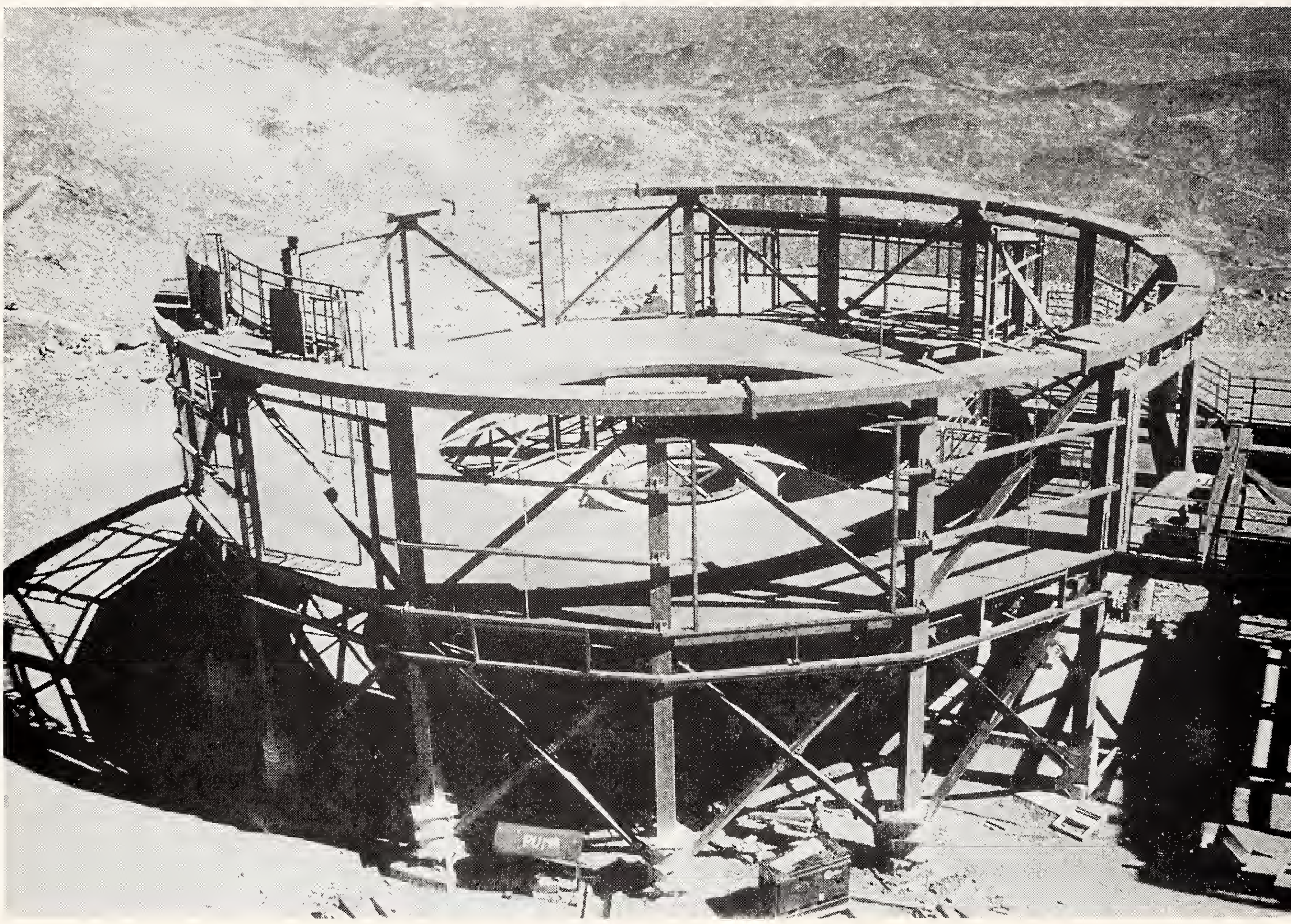


The fixed portion of the enclosure for the 6.5-meter Magellan I telescope under construction at Las Campanas, Chile. (Photo by Frank Perez, Magellan Project Lead Engineer, September 1995.)

Director's Introduction

As this is the last time that it will fall to me to write the introduction to the Carnegie Observatories' contributions to the Year Book, it may be a good opportunity to survey the main features of the last five years in the Observatories' life. The real life of the Observatories results from the free choices of the individuals who use the facilities to carry out research that seems to them to be of importance. Our tradition of free choice has continued to be cherished in the past five years. Not only Carnegie staff members, but also postdoctoral fellows, who have access to one-third of the telescope time on all our instruments, have been encouraged to follow whatever they find to be of the greatest interest and significance. The choices available to individual investigators are, nevertheless, determined by management decisions, by institutional policy, by the generosity of donors, and by the availability of federal support.

Since the facilities of Mount Wilson Observatory, under the bright night skies of Los Angeles, no longer could support research in dark-sky astronomy, the Carnegie Observatories in 1985 abandoned research at that site, and determined to concentrate efforts toward making Las Campanas Observatory in Chile a more powerful observing station. The most important feature of the last five years of the Observatories' life has been the progress of the Magellan Project. Now, in partnership with the University of Arizona and Harvard University, work is well advanced toward the completion of a 6.5-meter telescope for Las Campanas, and there are substantial hopes of completing the construction of a second telescope for the same site.

In order to concentrate resources on this endeavor, it was decided in 1995 to terminate our use of the Palomar 200-inch telescope, which Carnegie astronomers had enjoyed since it went into operation in 1948. This decision severely curtailed scientific opportunities for Carnegie

astronomers. The gap between losing access to the Palomar 200-inch and gaining access to the Magellan 6.5-meter, anticipated in 1998, might well have been a painful one. As it turned out, however, and quite by chance, the delay in fixing of the flawed optics of the Hubble Space Telescope gave Carnegie astronomers a well-timed opportunity to fill in the Palomar-Magellan gap.

In 1993 a newly active Mount Wilson Institute, under Robert Jastrow's leadership, started a program of renewal on Mount Wilson. New opportunities arose, such as research in adaptive optics, that made it possible to make good use of the excellent seeing conditions characteristic of Mount Wilson for specialized work that does not demand dark skies.

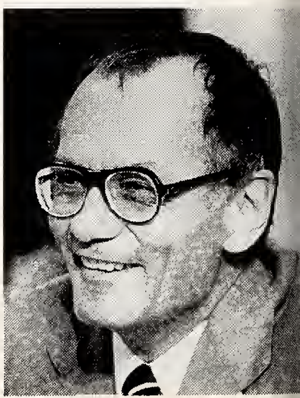
The three contributions to the Observatories' section of this Year Book illustrate some of these themes in the recent life of the Observatories. Jastrow reports on his achievements in bringing new life to an old observatory, while Wendy Freedman and Ray Weymann give accounts of some of the excellent use that Carnegie scientists are making of the Hubble Space Telescope.

—Leonard Searle

Second Light on Mount Wilson

by Robert Jastrow, Director, Mount Wilson Institute

A new operating agreement between Mount Wilson Institute and the Carnegie Institution of Washington, providing for management of the research facilities of Mount Wilson Observatory, went into effect on January 1, 1993. The agreement provided that Mount Wilson Institute shall "maintain, manage and operate the Observatory for scientific research, education and other projects in the field of astronomy." Since then, the principal objectives of the Institute have been to provide support for the research projects located on the grounds of the Observatory and to modernize and return to service the 100-inch Hooker Telescope, which had been decommissioned in 1985. The Hooker Telescope again became available to the astronomical community in the fall of 1994 and has since been used extensively by both in-house and guest observers.



Robert Jastrow

New observational programs have been selected to take advantage of the fine seeing at the site, which makes Mount Wilson an excellent

location for adaptive optics and interferometry. In place or under development are two adaptive optics systems at the 100-inch telescope and three interferometers working in the visible and infrared. The most recent facility designated for the site is an optical interferometer with a 400-meter baseline, to be constructed by Georgia State University; when completed, the GSU facility will be the largest optical interferometer in the world, with an angular resolution of 0.2 milliarcseconds.

Good Seeing on Mount Wilson

Mount Wilson is distinguished by excellent seeing typically and by spectacular seeing on occasional nights. Horace Babcock of the Carnegie Observatories, who measured seeing at Palomar, Mount Wilson, and other U. S. observatories, wrote that "Mount Wilson offers the best seeing of any North American observatory" (*Science 249*, p. 253, 1990). Babcock observed that on rare occasions r_0, the coherence length, achieved the value of 1 meter; this value corresponds to natural seeing of 0.1 arcseconds, a superlative condition.

Values of τ_0, the coherence time, at Mount Wilson are also exceptional. Data acquired at Mount Wilson with the Naval Research Laboratory interferometer indicate that τ_0 is greater than 10 milliseconds on 110 nights and greater than 15 milliseconds on 43 nights annually. These remarkable measurements mean improved performance for adaptive optics systems, while for interferometry they mean a roughly tenfold decrease in observing time and a corresponding advantage in productivity at Mount Wilson relative to other locations.

Adaptive Optics at the Hooker Telescope

In 1952 Horace Babcock proposed an innovative method for reducing the blurring effect of the Earth's atmosphere on rays of light from astronomical objects. The key elements of the system described by Babcock were a wavefront sensor, to sense the disturbances in the incoming beam, and an auxiliary "deformable" mirror, capable of changing shape rapidly according to instructions from the wavefront sensor, thereby correcting for the atmospheric disturbances. The method, which has come to be known as adaptive optics, offers the promise of making ground-based telescope images as sharp as images acquired from telescopes in space.

Adaptive optics systems based on the Babcock concept are in place or under development at a number of major observatories in the United States and abroad. In 1994, Christopher Shelton began work on an adaptive optics system for the 100-inch Hooker Telescope on Mount

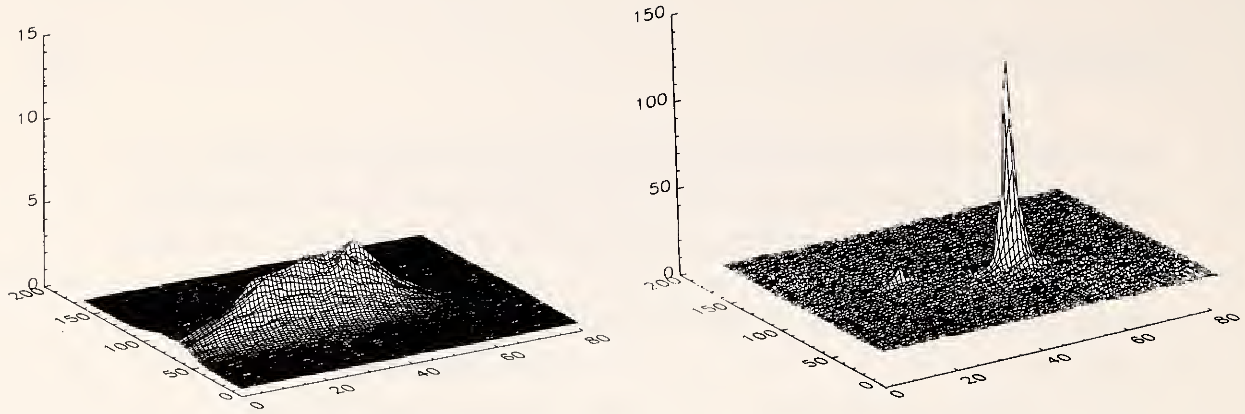


Fig. 1. Representation of the image of binary star τ Cygni, without (at left) and with (at right) adaptive optics. Intensity (vertical dimension) is plotted against area of sky (in pixels). In the left-hand plot, the cat under the rug is the binary's telescope image blurred by passage through the atmosphere. In the right-hand plot, the light from the sky is focused by the adaptive optics system to a small area of high intensity; the smaller peak to the left is the relatively faint binary companion, separated by 0.755 arcseconds. (The left-hand plot is magnified ten times in vertical scale.)

Wilson. The system was installed at the telescope in summer 1995, and has already yielded a better than tenfold improvement. The latest results, in September 1995, showed stellar images with a full width at half maximum of 68 milliarcseconds—close to the diffraction limit of the Hooker Telescope at visible wavelengths. The improvement in stellar images of the binary τ Cygni is shown in Figure 1. Upon further improvements in the speed of the system, the resolution of images with the Shelton system is expected to approach full width at half maximum of 50 milliarcseconds in visible light.

Several lines of research are planned with the 100-inch adaptive optics system. Most depend on coupling the adaptive optics output to a high-resolution spectrograph. Among the interesting possibilities are the following.

Stellar Spectroscopy. In applications requiring high spectral resolution, adaptive optics are useful for (1) increasing the Strehl ratio, which will improve signal-to-noise ratio for a given exposure time and also allow observation of fainter stars, increasing the number of stars accessible and the productivity of the system, and (2) improving the stability of the photocenter of the telescope pupil on the spectrograph slit, which, in turn, results in improved precision in measuring very small Doppler precision shifts.

Stellar Seismology. The five-minute acoustic oscillation modes have velocity amplitudes on the surface of the Sun of < 20 cm per second, which are detectable as Doppler shifts in disk-integrated sunlight. These five-minute solar oscillations were first discovered by astronomers working at Mount Wilson. Their discovery is perhaps the most important advance in solar physics in the last fifty years. They are frequently called seismic oscillations because their properties reveal the structure of a star's interior, much as seismic waves reveal the structure of the Earth's interior.

The great value of the five-minute oscillations in yielding

information on the solar interior provides strong motivation for attempting to detect the five-minute oscillations in other stars. However, seismic oscillations have not yet been detected in other stars because the motions and corresponding Doppler shifts are so small.

The increased precision obtainable with adaptive optics at the 100-inch telescope should provide the capability needed for detection of these oscillations.

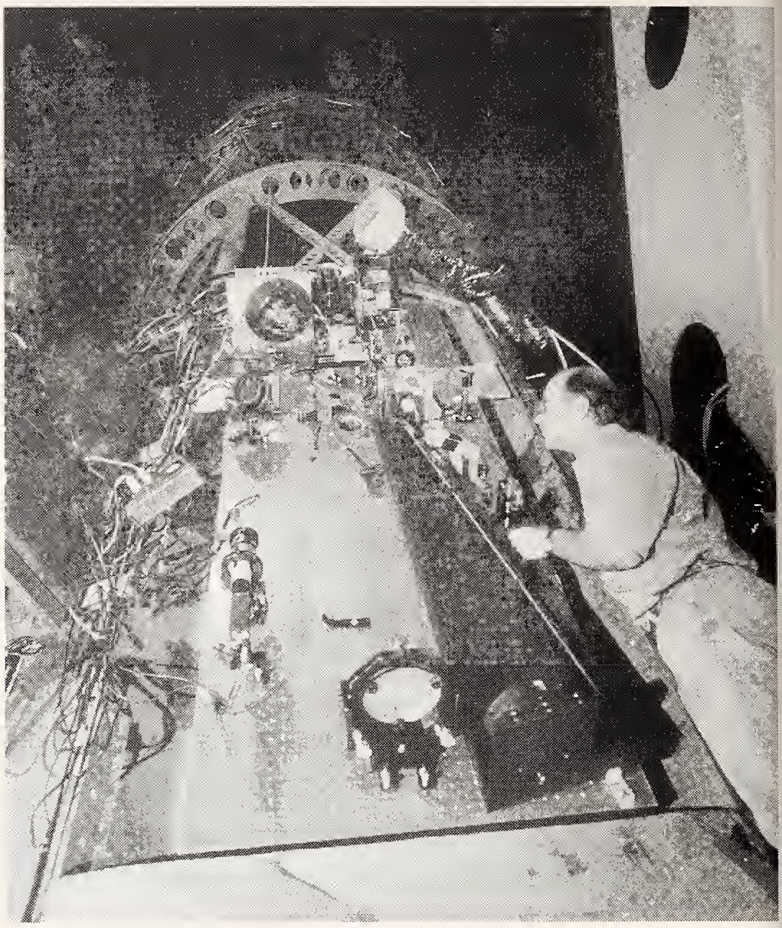
Ultra-High-Resolution Stellar Spectroscopy. The single-mode fiber from the adaptive optics system can feed the pit spectrograph of the 150-foot Solar Tower, requiring a suitable detector and coupling to the spectrograph slit. The pit spectrograph offers dispersion of 12.9 mm/Å and extremely good thermal and vibration control. The inherently high performance of the Solar Tower spectrograph without an adaptive optics system thus becomes even better with one.

Search for Planetary Companions of Nearby Stars. The presence of a planetary companion is revealed by periodic shifts in the spectral lines of its parent star, reflecting the motion of the star and planet around their center of mass. Doppler velocity measurements of extremely high precision, on the order of 1 meter per second, are required over a period of years in order to detect these periodic displacements. The adaptive optics system can provide the needed precision.

Orientation of Extra-Solar Planetary Systems. Space-based interferometers have been proposed as a means of detecting planetary systems around nearby, Sun-like stars. Efficient search techniques with these instruments require knowledge of the angle of inclination of the planetary system to our line of sight, which is assumed to be closely correlated to the orientation of the spin axis of the star. The orientation of a star's rotation axis can be inferred from existing measurements of rotational periods combined with high-resolution measurements of the Doppler shift, i.e., the rotation velocity projected to our line of sight, which can be obtained with the 100-inch adaptive optics system.

The 100-inch Modernization Program

The installation of adaptive optics on the 100-inch telescope is the latest step in a program for refurbishment and upgrade of the telescope and supporting instrumentation. Other accomplishments to date include the following. (1) *Electrical system*: the existing solenoid relays and switches were bypassed with power transistors and rectifiers governed by a microprocessor control unit. (2) *Drives*: encoders, controllers, opto-isolated solid-state relays for power switching, and communication hardware and software were installed; the telescope is controlled by a 486 computer. (3) *Mercury bearings*: after a thorough environmental scrubbing to remove any residual droplets that had seeped from the bearings, the bearings were dismantled and rebuilt in



Chris Shelton adjusts the adaptive optics system mounted on a 3′ × 9′ optical bench at the bent Cassegrain focus of the Mount Wilson 100-inch telescope. The deformable mirror is at the upper left. The rack at middle left holds the electronics for the system.

1993; an outer shell of fiberglass and a double-wall containment structure now surround the bearings and effectively isolate mercury and its vapor from human contact.

All other major mechanical and optical elements of the telescope are in excellent condition and require no work beyond routine maintenance.

Adaptive Optics Using Laser Guide Stars

Adaptive optics requires a guide star—either the target star itself or, if that is too faint, a brighter star nearby—as the source of light monitored by the wavefront sensor for atmospheric disturbance. It is also possible to use an artificial guide star, generated by reflection of a laser beam from the upper atmosphere. A project directed by Laird Thompson of the University of Illinois is developing a laser guide star adaptive optics system of this type, for installation at the 100-inch telescope on Mount Wilson. The system will increase sensitivity for observation of faint sources, opening the possibility of programs in extragalactic astronomy at the 100-inch. Initial operation is expected to begin in the 1997–1998 period.

The U. C. Berkeley Infrared Interferometer

In addition to the two adaptive optics systems in place or under development at the 100-inch telescope, also sited at Mount Wilson (since 1988) is an infrared interferometer project under the direction of Charles Townes of the University of California at Berkeley. The U. C.

Berkeley Infrared Spatial Interferometer (ISI), built by Townes with Manford Bester and Willliam L. Danchi of Berkeley, continues to obtain new observations and, as described below, will be expanded from two telescopes to three.

The two-telescope interferometer recently made the first measurements of stellar diameters in the mid-infrared; these reveal that because of "limb-darkening" past measurements of stellar size at visible wavelengths have been smaller than when measured in the infrared, where limb-darkening is minimized.

In addition, a new burst of gas and dust formation from the star α Orionis in late 1994 has been detected. Previous ISI measurements had shown that this star emitted a large amount of dust about a century ago but has since emitted very little. This very recent burst of dust generation is substantially smaller than the earlier one, but is the first one seen during actual formation.

ISI has so far operated with two telescopes mounted in trailers and movable to various separations and orientations. A third telescope, recently funded by the National Science Foundation, upon completion within two years will allow measurement of an astronomical object while simultaneously employing three different baselines or telescope separations. The maximum baseline with the expanded array will be increased from the present 32 meters to 85, nearly tripling the resolution. The third telescope should also allow "phase closure"—a measurement of the relative phase of interference fringes, which yields two-dimensional images of the objects observed.*

The CHARA Interferometer

Largely because of the excellent natural seeing, Mount Wilson Observatory has been selected as the site for an optical interferometer project under the direction of Harold McAlister of Georgia State University. The project, known as CHARA (Center for High Angular Resolution Astronomy), entails a Y-shaped array of from five to seven one-meter telescopes; the 100-inch Mount Wilson telescope could possibly be added to the array later. The CHARA telescope array will be laid out within a circle of approximate radius 400 meters. Resolution with this baseline is 0.2 milliarcseconds in the visible, which should permit resolution of the majority of known spectroscopic binaries. The result will be a large amount of new information relating to stellar masses, diameters, effective temperatures, and orbital parallaxes.

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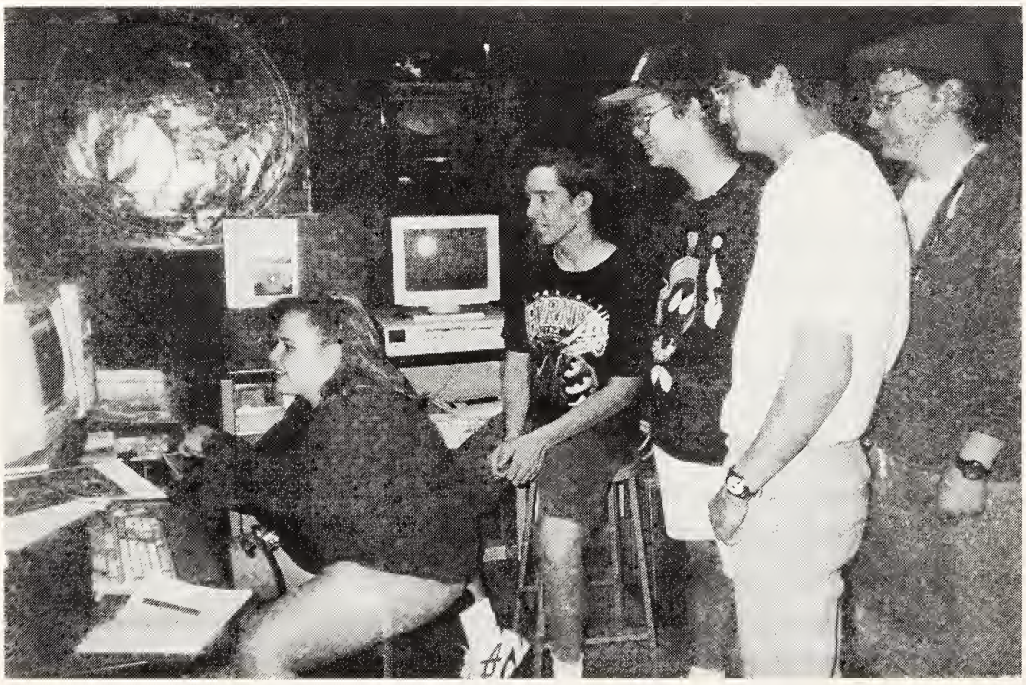
*An optical interferometer with a 30-meter baseline was in operation on Mount Wilson until 1993 as a joint program of the Naval Research Laboratory and the Jet Propulsion Laboratory. The project is currently inactive because of NRL concentration on a new project in New Mexico, but may be reactivated at a future date.

Science Education on Mount Wilson

Although research is the primary focus of the Observatory's program, the staff also has a strong interest in science education. An extraordinarily successful program, developed by Gilbert Clark of the Jet Propulsion Laboratory working with the Mount Wilson Institute, enables students at remote locations anywhere in the world having a computer and modem to dial up a research-grade 24-inch telescope on Mount Wilson, control the telescope as if the student were in the dome, point it at the star or galaxy of his or her choice, take an exposure with the CCD camera mounted on the telescope, and download the digitized image over the phone line to the student's home or school computer. A filter wheel, also controlled by the software, is available for obtaining color images from remote locations.

Every educator who has used the program reports that it is a powerful motivating force for generating student interest in science. Thus far the system has been used by 65 schools in 26 states across the United States and by schools in Japan, England, and Australia. We expect to add telescopes in Australia to the system, so that students in daytime classes in the U.S. can view the nighttime skies in the Southern Hemisphere, vice versa for students in Australia.



Students at Thomas Jefferson High School, Virginia, control the 24-inch telescope on Mount Wilson by computer and modem.

The Hubble Space Telescope and Measuring the Expansion Rate of the Universe

by Wendy L. Freedman

Near the turn of this century, Harvard astronomer Henrietta Leavitt was set to work on measuring the brightnesses of stars in a class known as Cepheid variables. Her sample of stars was located in the Small Magellanic Cloud, a diffuse-looking nebula (from the Latin word "fuzzy"), visible in the Southern Hemisphere and named after the explorer Ferdinand Magellan. A careful and obviously alert worker, Henrietta Leavitt not only measured the brightnesses of these stars, she also discovered an amazing property of Cepheids that was to have profound consequences for both stellar astronomy and cosmology in the 20th century. Leavitt's discovery led to the most accurate means that astronomers today have for measuring cosmic distances.

Wendy Freedman

The subsequent course of events is well known. In the mid-1920s, armed with Leavitt's new tool for measuring distances, Carnegie astronomer Edwin Hubble discovered Cepheid variables in several other nebulae and established that these objects were located far outside the confines of our Milky Way. Moreover, his results indicated that the nebulae he studied were systems not unlike our own Milky Way Galaxy in size and structure. Having established the existence of other galaxies, Hubble then went on in 1929 to make an even more remarkable discovery. The astronomer Vesto Slipher had been making measurements of the velocities of nebulae. Hubble discovered that galaxies for which he had measured large distances appeared to be systematically moving away from the Milky Way Galaxy at enormous velocities, whereas the galaxies at closer distances also appeared to be receding from us but at a slower rate. That is, Hubble discovered a correlation between the distance of a galaxy and its recession velocity. This relationship is now known as the Hubble law, and the constant of proportionality between the distance and velocity is known as the Hubble constant. The consequences of this relationship upon our understanding of the evolution of the universe have been enormous.

Earlier in the century, Albert Einstein had developed his General Theory of Relativity. Within the context of this theory, several theoreticians (notably Georges Lemaître, Willem de Sitter, and Alexander Friedmann) had investigated different models for the evolution of the universe. One class of potential solutions to Einstein's

equations allowed for the possibility that the universe was expanding (or contracting). Einstein dismissed this possibility (as had all other scientists before him) because there was no evidence that the universe was in motion; the universe was believed to be static. But Hubble's observations provided compelling evidence to the contrary. Together, theory and observations led to a model for the evolution of the universe which is known today as the Big Bang model.

Big Bang cosmology makes a number of predictions. In a uniformly expanding universe, galaxies would have been closer together in the past. Early in the universe, the density (and temperature) of matter would therefore have been very high. Hubble's law, the subsequent discovery of a (now) cool remnant cosmic background radiation, and the observed densities of the lightest elements (for example, hydrogen and helium) all provide evidence in support of the Big Bang model. One of the simplest versions of this theory, known as the Einstein–de Sitter model, has become the standard working hypothesis. It makes a number of testable predictions about the observable properties of the universe (for example, its age and its average density).

It remains for observational astronomers to test these predictions. A solid measurement of the expansion rate (or Hubble constant), together with an independent estimate of the ages of the oldest objects in the universe and a measurement of the average density in the universe, are all separately required in order to make these tests and provide constraints on cosmological models.

Measurement of the expansion rate is important for other reasons. Knowledge of the Hubble constant is required to determine many intrinsic properties of galaxies and clusters of galaxies (e.g., their masses, luminosities, scale sizes), and hence to provide a necessary foundation for the eventual understanding of how these objects formed. Understanding the growth of structure in the early universe, estimating the density of light elements in the early universe, and determining the size and age of the visible universe all require a determination of the Hubble constant.

Measurement of the Hubble Constant

Although measurement of the Hubble constant is extremely simple in principle, it is extraordinarily difficult in practice. The Hubble constant is given simply by the ratio of two measurements: a galaxy's velocity and its distance. Why then has the measurement of the Hubble constant remained an outstanding problem in cosmology for 66 years after Hubble's original discovery? It is certainly not for lack of hard work or creative ideas. Beginning with Carnegie astronomers Edwin Hubble, Walter Baade, and Allan Sandage, and continuing up to the present day, many astronomers have invested enormous amounts of

time trying to measure accurate distances to galaxies with the aim of determining an accurate value for the Hubble constant.

There are two main reasons why the problem has persisted. First and foremost, establishing an accurate extragalactic distance scale has turned out to be enormously more difficult than anticipated. Second, while the velocities can be measured simply and accurately, a galaxy's velocity may not represent very well the expansion velocity of the universe at that distance. The reason is simple: galaxies interact gravitationally with their neighbors, such that their velocities are perturbed (inducing "peculiar motions"); thus a measured velocity can be either greater or less than that due to the general expansion of the universe. In addition, the work of Carnegie astronomer Alan Dressler, Carnegie Fellow Jeff Willick, and colleagues (including Carnegie trustee Sandra Faber) indicates that on very large scales, galaxies may be participating in coherent motions, or "flows," which are also unrelated to the Hubble expansion. Hence, an accurate measurement of the Hubble constant requires not only that an accurate extragalactic distance scale be established but also that it be established at distances great enough that peculiar motions of galaxies are small compared to the overall cosmic expansion velocity. The task has grown into an enormous undertaking.

For the dedication of the University of Michigan Curtis Telescope in 1951, Carnegie astronomer Walter Baade wrote: "Altogether there are good reasons to believe that the solution of the cosmological problem is much more difficult than was thought some fifteen years ago and that it may well lie beyond our present powers. Certainly we need better-secured foundations than at present, before we can hope to erect big superstructures."

Baade was right. In 1952 he established that an error in the luminosity scales available to Hubble had resulted in an error in the distance scale amounting to a factor of two. Later, in the mid-1970s, Allan Sandage demonstrated that some of the "brightest stars" in galaxies, used by Hubble to estimate distances, were in fact luminous HII-region complexes (regions of ionized hydrogen gas surrounding bright stars). The necessary revision in the distance scale also was by approximately a factor of two. Finally, in the past two decades, Caltech astronomer Barry Madore and I have established that the presence of dust in the spiral galaxies where Cepheids are located significantly dims and reddens these stars, thereby also causing a systematic error in the distance scale, which must be recognized and accounted for. Coupled with a correction for remaining errors in the earlier photographic luminosity scales, our revisions have recently led once again to a factor-of-two change in distances to Cepheid galaxies. However, this time the corrections were found to be in the opposite direction to the revisions of Baade and Sandage.

What is the current status of the extragalactic distance scale? The most accurate means that astronomers have at present for measuring distances remains the Cepheid variables and their period-luminosity relation discovered by Henrietta Leavitt. Over the last decade, a number of checks on the period-luminosity relation have been made, and distances to the nearest galaxies have been measured using both Cepheids and various other methods. These nearby distances are now found to be in excellent agreement. If it were feasible, Cepheids would be used to measure distances out into the Hubble flow directly. Unfortunately, to date it has not been possible to detect Cepheids in galaxies that are sufficiently distant to participate in the pure Hubble expansion, essentially unaffected by the peculiar motions discussed above. Meanwhile, several other methods have been developed for measuring the relative distances among galaxies.

Relative distances, however, cannot alone provide a measure of the Hubble constant. The situation is very much like the case of an ordinary road map with no scale printed on it. We could establish, for example, that two given cities are closer to each other than to a third city. But if we don't know the scale of the map, then we have no knowledge of the actual distances between given cities; there could be tens or hundreds or thousands of miles between them. Similarly, to measure the Hubble constant, we require a knowledge of the actual, or "absolute," distances to galaxies, not just their relative distances. Following the analogy of a road map, if we know the absolute distances between any two cities on the map, then the absolute distances between all other cities are established. The relative distances can be "calibrated." The Cepheid distance scale provides just such an absolute calibration.

In the last decade enormous progress has been made in developing "secondary" methods for measuring relative distances on vast scales, well beyond the range of the Cepheids. These methods include measuring the brightnesses of supernovae—the powerful, explosive deaths of stars. Allan Sandage and collaborators are currently undertaking a Space Telescope program to determine the Hubble constant based on the Cepheid calibration of one type of supernova. Other methods include measuring the brightnesses and rotational velocities of entire galaxies, the fluctuations or graininess in their light, and the measurement of another class of younger, more massive supernovae. The key now for measuring the Hubble constant is to determine the distances to selected galaxies containing Cepheids; these known distances can, in turn, be used to calibrate the relative extragalactic distance scale and make it absolute.

For decades, it has been recognized that observations at very high spatial resolution would be required. Although Cepheids are among the brightest stars, identifying these individual stars against the bright

background of other stars in a host galaxy is feasible only for the very nearest systems. The reason is that the Earth's atmosphere is in turbulent motion, blurring and smearing out light reaching telescopes on the ground. Finding or recognizing individual Cepheids beyond a certain distance is not possible. One of the primary motivations for building an optical telescope in space was to find Cepheids in more-distant galaxies, opening the way to pin down an accurate value of the Hubble constant. Eagerly awaited for decades, the Space Telescope was launched in 1990 and named in honor of Edwin Hubble.

The Hubble Space Telescope Key Project on the Extragalactic Distance Scale

Given the difficulty in measuring galaxy distances, it is obvious that there are several fundamental issues that must be addressed and tests that must be designed to identify other potential remaining sources of error. It was with these difficulties clearly in mind that a team including myself and thirteen internationally based collaborators submitted a proposal for the "Key Project on the Extragalactic Distance Scale." (Key Projects were designated in a peer-review process as high-priority programs for the Hubble Space Telescope. Another Key Project is the study of the evolution of hydrogen gas clouds in the universe, described in the following article by Ray Weymann, p. 148.)

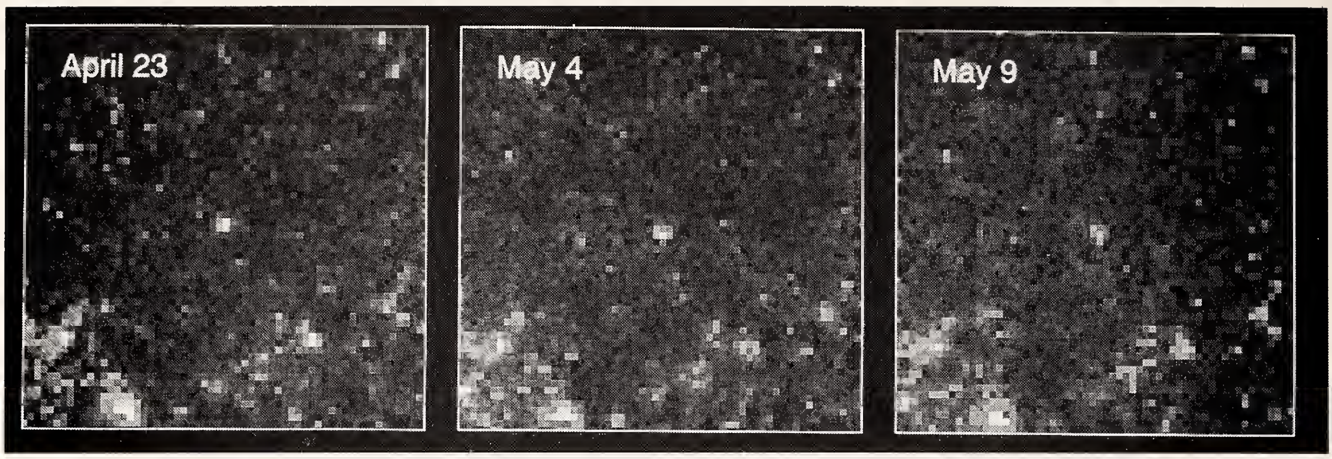
The three aims of our Key Project are:

(1) to measure the Cepheid distances to a sample of about twenty galaxies. These galaxies were chosen explicitly for the purpose of calibrating five secondary methods for measuring the relative distances to galaxies. Four of these methods can be applied to galaxies remote enough that peculiar motions do not significantly affect the Hubble velocity.

(2) to measure Cepheid distances to galaxies located in two of the nearest massive clusters of galaxies, Virgo and Fornax.

(3) to undertake a number of tests and cross-checks—for example, testing for systematic errors in the Cepheid distance scale and comparing several secondary methods in the course of undertaking (1) and (2) above.

What is the physical nature of a Cepheid's variability, and how are these stars used to measure distances? Cepheid variables are bright, young stars with masses perhaps five to twenty times that of our own Sun. The presence of a zone of ionized helium in the outer atmosphere of a Cepheid is responsible for setting its atmosphere in motion: the atmosphere alternately contracts and expands in response to the competing, but temporarily imbalanced, forces of gravity pulling inward and the pressure of hot gas pushing outward on the atmosphere of the star. The brightness of a Cepheid changes regularly



1994 HST photos show rhythmic changes in the brightness of a Cepheid variable star in the spiral galaxy M100. This Cepheid doubles in brightness (24.5 to 25.3 apparent magnitude) over a period of 51.3 days. Credit: Wendy Freedman and NASA.

over the course of its radial pulsation cycle. Henrietta Leavitt discovered that as a Cepheid changes in brightness, it does so at a rate proportional to the overall brightness of the star, a correlation that is now referred to as the Cepheid "period-luminosity relation." Brighter Cepheids vary on longer timescales (i.e., have longer periods) than intrinsically fainter Cepheids. Once the period-luminosity relation was itself calibrated (using measurements by other means to a sample of nearby Cepheids), it could be used to give absolute luminosity (and distance) to all measurable Cepheids, simply using the inverse square law of light. Hence, the main task of the Key Project is to discover Cepheids in other galaxies, measure their periods and brightnesses, and thereby measure the distances to these galaxies.

All three aspects of the Key Project are now well under way. At the end of the first of our three years, our team had discovered about 300 new Cepheid variables in six galaxies. Most of these galaxies will provide distances critical for calibrating secondary distance methods. In one case, we have measured samples of Cepheids in two different locations within the same galaxy, allowing us to undertake a test of the potential sensitivity of the Cepheid period-luminosity relation to chemical composition. In addition, we have measured a Cepheid distance to the galaxy known as M100, which is the first of three galaxies in our sample located in the nearby Virgo cluster.

Our measurement of the Cepheid-based distance to a galaxy in the Virgo cluster was a critical step. Although in the past decade the distances to nearby galaxies measured by different techniques have come into good agreement, in the case of the Virgo cluster published values of distance have differed by up to a factor of two. The uncertainty persisted because no direct Cepheid distance measurements were feasible from the ground: even with the highest resolution achievable from the ground, it was not possible to unambiguously identify Cepheids at the distance of the Virgo cluster. Upon our initial discovery of twenty Cepheids in M100 (and now a sample of approximately fifty), we have been able to measure accurately the distance to this galaxy, and then to obtain a value of the Hubble constant from it, with a final uncertainty of 20%. The uncertainty results from the fact that we have, to date, measured the

distance to only one galaxy in the Virgo cluster, and also because the Virgo cluster itself is still not far enough away to be entirely free from uncertainties in its overall expansion velocity. (Our own Galaxy is infalling into the cluster, and this effect needs to be understood and corrected for.) However, our result is based on the most accurate and most direct distance determination to date for a galaxy in the Virgo cluster.

It is still too early to tell what the final outcome will be. Most of the Key Project data are not yet in; many observations have not yet been made. However, our preliminary result is that the value of the Hubble constant is 80 kilometers/sec per Megaparsec of distance.* If confirmed (and our most recent preliminary results appear to be consistent with it), this value has major implications. It is in conflict with the predictions of the standard Einstein–de Sitter model discussed in the introduction to this essay, given the current best estimates for the ages of the oldest objects in our own Galaxy, the globular clusters. Our expansion rate yields a value for the age of the universe of between 8 and 12 billion years, producing an immediate paradox, since the globular clusters, with ages of about 15 billion years, would appear to be older than the universe. It is plainly important to improve the accuracy of both of these age estimates. If both values are eventually confirmed, the Einstein–de Sitter cosmological model would be ruled out.

The next two years of the Key Project will be critical. The project has been designed to confront outstanding discrepancies, to test for potential systematic errors, and to measure and compare values of the Hubble constant based on many different methods. Our most recent results show that the measurement of Cepheid distances at the distance of the Virgo cluster is feasible, and that the entire Key Project is viable. Moreover, with Carnegie astronomer Eric Persson, Barry Madore and I are re-doing the fundamental calibration of the Cepheid period-luminosity relation using telescopes at Las Campanas and Palomar. From the ground, several other groups are continuing to extend the measure of relative distances using secondary methods. These groups are making use of existing and new large telescopes being constructed on the ground, eventually to include Carnegie's new 6.5-meter Magellan I telescope. The recent progress in this field has been enormous. Now, in addition, with the availability of the Hubble Space Telescope and our first results, there are good reasons that make me very optimistic that within the next few years we will have solved one of the outstanding cosmological problems of this century.

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*1 Megaparsec = 3.26 million light years. Thus, an object 3.26 million light years from us will recede at 80 km/sec.

The Hubble Space Telescope and the Evolution of the Gaseous Content of the Universe

by Ray Weymann

The obvious frustration of waiting several nights for storm clouds to pass at a ground-based observatory may seem reason enough for astronomers to rejoice at the opportunity to use the Hubble Space Telescope (HST), but the fundamental reasons for the vital role it now plays in astronomical research are otherwise. First, orbiting above the atmosphere, it is able to obtain images of astonishing clarity and sharpness. The use of this imaging capability in visible light to determine the basic distance scale of the observable universe is described in the preceding article by Wendy Freedman. Second, the HST is above the layer of ozone and other gases in the atmosphere which prevent ultraviolet radiation from reaching the ground (despite modern civilization's potentially catastrophic tampering with this layer).

Observations of this ultraviolet radiation with the two spectrographs now operating on board HST have provided us with our first look at relatively nearby uncondensed gas in exactly the same way that spectrographs on ground-based telescopes have provided us with information on the nature of gas at very large distances from us (Michael Rauch, *Year Book 93*, pp. 142–147). The apparent paradoxical situation—that an ultra-sophisticated orbiting telescope is required to study at relatively nearby distances what ground-based telescopes study at large distances—can be traced to the fact that we live in an expanding universe: very distant objects are all moving away from us with speeds proportional to their distance. Hydrogen gas, detected from its interaction with ultraviolet radiation, has been observable at great distances because the ultraviolet is Doppler-shifted (redshifted) to reach us as visible light, not blocked by the ozone layer. But in the case of relatively nearby gas, the more modest redshift of the radiation still leaves it unable to penetrate the Earth's atmosphere, and therefore studying this material has only been possible since the launch of HST.

Ray Weymann

The Context: Cosmology and the Growth of Structure

Before describing some of the details of this work, it is appropriate to consider this topic in the context of some broader fundamental

questions in modern astronomy. There is now overwhelmingly strong evidence that the universe (or at least that portion of it which we can ever hope to investigate observationally) began in an exceedingly hot dense phase. Helium and hydrogen atoms, together with the cooled remnants of the so-called "fireball radiation," were generated during the brief early moments of this phase, as described, for example, by Steven Weinberg in his book *The First Three Minutes.** As far as we are aware, this phase and the subsequent evolution of the universe can, in principle, be correctly described within the theoretical framework of Einstein's General Relativity Theory.

The simple models for the expanding universe, based upon General Relativity, describe an idealized homogeneous and isotropic universe. A glance around, however, quickly convinces one that the universe is today highly non-uniform. Recent results from the COBE satellite have detected departures from uniformity in the remnant fireball radiation. These measurements refer to epochs long after the "first three minutes" but also long before the first stars and galaxies are thought to have condensed. Moreover, the departures from uniformity are exceedingly small.

Thus, in the interval of time between the COBE measurements and the present, all the complexity of the universe we see today must have developed. Interestingly, therefore, understanding the development of structure is one of the fundamental current problems in astronomy just as it is in the biological sciences.

But the problem of the development of structure is coupled with other equally fundamental questions. The expanding universe models allow for a range of behavior: some model universes are continually expanding and infinite in volume, others eventually cease expanding and recollapse and are finite in volume. A critical factor in deciding which of these idealized models comes closest to describing our actual universe involves the amount of material that is able to interact gravitationally. There is growing evidence that hydrogen and other constituents of ordinary (baryonic) matter account for only a small fraction of the gravitationally interacting matter. Thus, most of the universe may consist of non-baryonic matter—particles which interact only through gravitational interaction, do not give rise to radiation, and are not part of the makeup of stars, planets, or ourselves. The hope motivating much of today's astronomical research is that the interplay between the development of structure and the composition and geometry of the universe will allow us to sort out and understand all of these issues.

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*Steven Weinberg, *The First Three Minutes: A Modern View of the Origin of the Universe*, second edition, Basic Books, New York, 1993.

Uncondensed Hydrogen in the Recent Universe

Our interest in studying nearby gas is not only in its relative nearness but also in the fact that the radiation which interacted with such gas left it relatively recently. Combining data from both ground-based and HST observations allows us to trace the history of this gas over a significant fraction of the age of the universe. In fact, the HST observations cover about the last 60% and the ground-based observations only about the previous 20%. (In the final section of this essay, I will describe a new instrument to be placed on the HST in 1997 which may provide information on portions of the earliest 20%.) The HST observations clearly play a vital role in filling this history.

In addition, however, the nearness of the low-redshift gas allows examination of a crucial property which is virtually impossible in the high-redshift gas: does the gas fill space uniformly without any affinity for ordinary galaxies or is it intimately associated with, or even an extension of, galaxies? If the latter, with what kinds of galaxies is it associated?

Prior to the launch of HST, ground-based observations of the uncondensed hydrogen at large redshifts established that the gas was distributed in clouds rather than smoothly, but that the clouds themselves were distributed fairly uniformly rather than strongly in clusters (in the way that galaxies are at the present time). This fact, together with the absence of any evidence for heavy elements (all of which besides hydrogen and helium are synthesized in stars) led to the suggestion that this gas was primordial—it had never been associated with galaxies nor had ever been inside stars in galaxies, and perhaps never would be. It was further speculated that these clouds were held together by the external pressure of very much hotter hydrogen. As described by Rauch in *Year Book 93*, the study of these clouds is carried out by observing a background quasar against whose spectrum the absorbing hydrogen gas is imprinted as a series of absorption lines. As one examined the frequency with which our line of sight to the quasar intercepted the clouds, it became clear that the "forest" of absorbing clouds rapidly thinned out as the redshifts became lower and lower, until the atmospheric ozone cutoff obscured still-lower-redshift clouds.

Simply extrapolating this trend to the present epoch, there was some concern that nearby clouds would be so rare that they would be difficult to study with HST. To our relief and surprise the first observations made by myself and colleagues on the High Resolution Spectrograph (HRS) instrument team and by another group using the Faint Object Spectrograph (FOS) toward the bright quasar 3C273 found a substantially larger number of absorbing clouds than expected on the basis of simple extrapolation of the ground-based data. (Theorists now

tell us there are many ways to understand this, and that it should not have been all that unexpected—but theoretical astrophysicists are notorious Monday morning quarterbacks.)

In advance of this result it was anticipated that study of these low-redshift clouds would be a crucial mission of HST, and such a study was designated a Key Project prior to the launch of HST. Subsequent observations by myself and my colleagues on this team, as well as numerous independent HST and supporting ground-based observations of galaxies, have led to the following tentative results.

(1) The thinning-out of the absorbing clouds seen in the ground-based observations of the distant high-redshift clouds continues at low redshifts, but at a much gentler rate than at high redshifts. It has yet to be established whether there is a smooth or rather abrupt change in the rate of this thinning-out.

(2) There is strong statistical evidence that these low-redshift clouds are in fairly close physical proximity to galaxies—closer than might have been expected from observations of the high-redshift clouds. (But it should be recalled that only exceedingly luminous galaxies associated with the high-redshift clouds can be detected and their redshifts measured, so this difference is only inferential.) The tendency for physical proximity to galaxies seems to become weaker as the strength of the absorption associated with a cloud becomes weaker.

(3) Recent measurements by colleagues at the University of Arizona and myself of both high- and low-redshift clouds (using both ground-based telescopes and HST) of absorption in pairs of quasars having small angular separations allow us to infer characteristic lateral dimensions of the absorbing clouds. These dimensions turn out to be much larger than early estimates and models suggested. In fact, they turn out to be comparable to typical separations between galaxies rather than being galaxy-sized themselves.

(4) Some recent HST Key Project observations show remarkable clumps of these absorbing clouds, which are suggestive of the clumping one observes from a large cluster of galaxies. These clumps are sometimes accompanied by a large thick cloud possibly associated with a dominant galaxy in the possible cluster.

There has been considerable speculation concerning the interpretation of these facts, especially of the statistical association between the clouds and galaxies. One popular interpretation is that the clouds are actually embedded in gigantic halos surrounding very luminous galaxies. It is not clear, however, what the embedding mechanism is. Moreover, an unambiguous identification linking an absorbing cloud with a particular galaxy is difficult to make in a significant fraction of these clouds: in many cases we simply do not recognize the galaxy with which the cloud is associated. Recently, Carnegie research associate Michael Rauch, Simon Morris (a former

Carnegie research associate now at the Dominion Astrophysical Observatory), and I attempted such identifications for two of the very nearest and best-studied absorbing clouds. In this case there are clearly no individual luminous galaxies with which these clouds can be unambiguously associated. Thinking that perhaps there might be underluminous dwarf galaxies closely associated with these clouds (such dwarfs would be much too faint to detect except for very nearby cases), we conducted a search for such dwarfs with the Palomar and Las Campanas telescopes, with negative results. What we found, however, is that there are loose groups of galaxies in the neighborhoods of these clouds. The interpretation which we favor for all but the stronger absorbing clouds is that they represent the uncondensed remnants or debris around structures which collapsed to form groups of galaxies.

One may ask whether these observations bring us any closer to an understanding of the cosmological questions posed at the outset. It is too early to be sure yet, but I am optimistic that the answer will turn out to be positive. This optimism is based in part on a development which is as dramatic (though less publicized) than the huge observational strides represented by HST and other modern astronomical instruments. In the four decades since I began graduate work in astronomy there has been an improvement of a factor of about ten billion in the rapidity with which arithmetic calculations can be carried out, with perhaps another factor of from 10 to 100 expected in a few more years. This has allowed the conduct of remarkably detailed three-dimensional numerical simulations of the growth of structure under a variety of basic cosmological assumptions. Some early results suggest that the mechanisms giving rise to the observed absorption are varied and complex dynamical processes, and lead to an interpretation not very different from the one described in the preceding paragraph.

NICMOS and the Earliest-Forming Galaxies

In this final section I will describe an opportunity offered by the HST which, it is hoped, will be realized in the near future. In 1997 another space shuttle servicing mission will visit HST and, if all goes as well as in the previous mission, the astronauts will replace two existing instruments with two new ones: a more powerful spectrograph (STIS) and the Near Infrared Camera and Multiple Object Spectrograph, or NICMOS, whose instrument team I am a member of. The reasons for wanting to place such an infrared instrument on HST are basically the same as described in the introduction to this essay: (1) The images should be much sharper than those that can be obtained from the ground, though the developing technique of "adaptive optics" may provide limited sharp imaging from the ground, and (2) One wishes to

be above the Earth's atmosphere to avoid the absorption in the infrared due mainly to water vapor. In addition, emission primarily from the hydroxyl molecule in the upper atmosphere causes the sky at even the darkest ground-based site to be much brighter than it is from space, making detection of very faint objects difficult.

There is an additional particularly attractive advantage. We have described, above, the possible residue or debris of matter that has not yet (and may never) condense into galaxies. What about the converse problem: When did the very first galaxies condense, and what were they like? Glimpsing the birth of such galaxies implies that we must look out in space and back in time to extremely high redshifts. Such high redshifts mean in turn that most of the radiation may not be in the form of ordinary visible light but will be shifted into the near-infrared spectrum. Even simple counts of the number of increasingly fainter galaxies with NICMOS will provide new information on galaxy formation and evolution. In addition, there are some distinctive trademarks which nascent galaxies might have, and our hope is that NICMOS will identify some likely candidates. Nascent galaxies are likely to be very rare and will require extensive searches, but simulations like the ones described above suggest that they exist.

The spectroscopic capabilities of NICMOS are rather limited, however (HST is, after all, still a comparatively small telescope), and to confirm the true nature of such candidates will require the use of the infrared spectrographs on the new generation of very large ground-based telescopes typified by those of Carnegie's Magellan Project now being erected on Las Campanas.

As in the case of the low-redshift hydrogen clouds described above, we cannot be sure what NICMOS will reveal. But the symbiosis of the Hubble Space Telescope, the new generation of large ground-based telescopes, and the new power of numerical simulation offer us a real hope of viewing—and comprehending—virtually the entire history of the development of the structure of our universe.

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Personnel

Research Staff

Horace Babcock, Emeritus
Alan Dressler
Wendy Freedman
Jerome Kristian
Patrick McCarthy
Eric Persson
George Preston
Allan Sandage
Leonard Searle, Director
Stephen Shectman
Ian Thompson
Ray Weymann

Staff Associate

Steve Majewski, Hubble Fellow

Postdoctoral Fellows and Associates

Julianne Dalcanton, Hubble Fellow[1]
Bob Hill, Research Associate
Stephen Landy, Research Associate
Andrew McWilliam, McClintock Fellow
John Mulchaey, Carnegie Fellow[2]
Randy Phelps, Research Associate[3]
Michael Rauch, Research Associate
Ian Smail, Carnegie Fellow[4]
Jeffrey Willick, Carnegie Fellow
Ann Zabludoff, Carnegie Fellow
Dennis Zaritsky, Hubble Fellow[5]

Las Campanas Research Staff

Wojciech Krzeminski, Resident Scientist
William Kunkel, Resident Scientist
Miguel Roth, Director, Las Campanas Observatory

Support Scientists

William Kells[6]
David Murphy
Anand Sivaramakrishnan

Supporting Staff, Pasadena

Joseph Asa, Magellan Electronics Technician[7]
Alan Bagish, Las Campanas Observatory Engineer
Richard Black, Business Manager
David Carr, Magellan Project Instrument Engineer
Ken Clardy, Data Systems Manager
Marinus de Jonge, Magellan Project Manager
Joseph Dizon, Instrument Maker[8]
Elizabeth Doubleday, Publications Editor
Joan Gantz, Librarian
Bronagh Glaser, Administrative Assistant
Karen Gross, Assistant to the Director
Matt Johns, Magellan Project Systems Engineer
Aurora Mejia, Housekeeper[9]
Roberto Mejia, Housekeeper
Kristin Miller, Magellan Project Administrative Assistant
Georgina Nichols, Controller[10]
Greg Ortiz, Assistant, Buildings and Grounds[11]
Stephen Padilla, Photographer
Gloria Pendlay, Administrative Assistant[12]
Frank Perez, Magellan Project Lead Engineer
Pilar Ramirez, Machine Shop Foreperson
Lorraine Renfroe, Staff Accountant[13]
Scott Rubel, Assistant, Buildings and Grounds
Jeanette Stone, Purchasing Agent
Robert Storts, Instrument Maker
Estuardo Vasquez, Instrument Maker
Steven Wilson, Facilities Manager[14]

Supporting Staff, Las Campanas

Eusebio Araya, Mountain Superintendent
Hector Balbontín, Chef
Emilio Cerda, Electronics Technician
Angel Cortés, Accountant
José Cortés, Janitor
Jorge Cuadra, Assistant Mechanic
Oscar Duhalde, Mechanical Technician
Julio Egaña, Painter
Gaston Figueroa, Small Shift Supervisor
Luis Gallardo, El Pino Guard
Juan Godoy, Chef
Jaime Gomez, Purchasing Agent
Danilo Gonzalez, El Pino Guard
Bruno Guerrero, Electronic Technician[6]
Luis Gutierrez, Mechanic[15]

Javier Gutierrez, Heavy Equipment Operator
Juan Jeraldo, Chef
Juan Luis Lopez, Magellan Project Supervisor[16]
Leonel Lillo, Carpenter
Mario Mondaca, Part-time El Pino Guard
Cesar Muena, Night Assistant
Silvia Muñoz, Business Manager
Herman Olivares, Night Assistant
Fernando Peralta, Night Assistant
Leonardo Peralta, Driver/Purchaser
Patricio Pinto, Electronics Technician[17]
Oscar Rojas, Janitor[18]
Roberto Ramos, Gardener
Demesio Riquelme, Janitor
Honorio Rojas, Water Pump Operator
Hernan Solis, Electronics Technician
Mario Taquias, Plumber
Gabriel Tolmo, El Pino Guard
Manuel Traslaviña, Heavy Equipment Operator
David Trigo, Warehouse Attendant
Patricia Villar, Administrative Assistant
Alberto Zuñiga, Night Assistant

Visiting Investigators

Gonzalo Alcaino, Instituto Isaac Newton, Chile
Rebecca Bernstein, California Institute of Technology
Leonardo Bronfman, Universidad de Chile
Harold Butner, Department of Terrestrial Magnetism
Bruce Carney, University of North Carolina
Rodrigo Carrasco, Universidad Católica de Chile
Andrew Connolly, Johns Hopkins University
Edgardo Costa, Universidad de Chile
Raul Cuza, Michigan State University
Mamoru Doi, National Optical Observatory, Japan
Wolfgang Gieren, Universidad Católica de Chile
John Graham, Department of Terrestrial Magnetism
Paul Harding, University of Arizona
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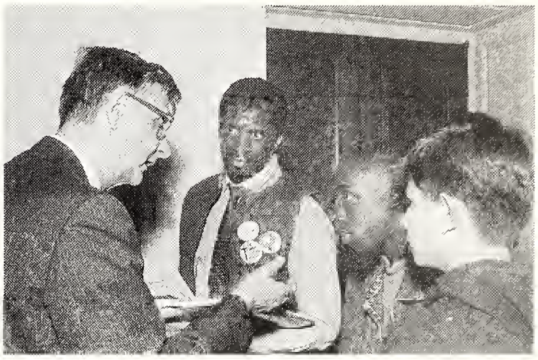
Janusz Kaluzny, Warsaw University
Nobunari Kasikawa, University of Tokyo
Marcus Kissler, Universidad Católica de Chile
Marcin Kubiak, Warsaw University
Arlo Landolt, Louisiana State University
Barry Madore, California Institute of Technology
Ashish Mahabal, Giant Meter-Wave Radio Telescope, Poona University, Pune, India
Mario Mateo, University of Michigan
Ronald Mennickent, Universidad de Concepción
John Middleditch, Los Alamos National Laboratory
Bryan Miller, Department of Terrestrial Magnetism
Edward Olszewski, University of Arizona
Michael Pahre, California Institute of Technology
Sheo Pandey, Giant Meter-Wave Radio Telescope, Poona University, Pune, India
Hernán Quintana, Universidad Católica de Chile
David Rabinowitz, Department of Terrestrial Magnetism
Michael Regan, University of Maryland
Neill Reid, California Institute of Technology
Monica Rubio, Universidad de Chile
Nicholas Schneider, University of Colorado
Maki Sekiguchi, National Optical Observatory, Tokyo, Japan
Jon Sievers, Massachusetts Institute of Technology
Deano Smith, University of Michigan
John Trauger, Jet Propulsion Laboratory, California Institute of Technology
Douglas Tucker, Yale University
Masafumi Yagi, University of Tokyo
Dennis Zaritsky, University of California, Santa Cruz

* * *

[1]From January 1, 1995
[2]From September 23, 1994
[3]From October 1, 1994
[4]NATO Fellow from January 1, 1995 to March 31, 1995; Carnegie Fellow from April 1, 1995
[5]To August 31, 1994
[6]To June 30, 1995
[7]From May 1, 1995
[8]To March 15, 1995
[9]From February 1, 1995
[10]From April 10, 1995
[11]From February 1, 1995
[12]To February 28, 1995
[13]To February 24, 1995
[14]From December 1, 1994
[15]To May 3, 1995
[16]From July 15, 1994
[17]From May 16, 1995
[18]From January 2, 1995

Extradepartmental and Administrative



1993 Capital Science Lecturer E. O. Wilson and students

Personnel

Office of Administration
1530 P Street, N.W.
Washington, D.C. 20005[1]

Lloyd Allen, Building Maintenance Specialist
Sharon Bassin, Secretary to the President
Sherrill Berger, Research Assistant, Institutional and External Affairs
Ray Bowers, Editor and Publications Officer
Gloria Brienza, Budget and Management Analysis Manager
Don A. Brooks, Building Maintenance Specialist
Cady Canapp, Human Resources and Insurance Manager
Margaret Charles, Secretary
Patricia Craig, Associate Editor
Nicholas DeCarlo, Grants and Operations Manager[2]
Susanne Garvey, Director of Institutional and External Affairs
Mary Ann Kaschalk, Financial Accountant[3]
Ann Keyes, Accounts Payable/Payroll Coordinator
Jeffrey Lightfield, Financial Accountant[4]
John J. Lively, Director of Administration and Finance
Lynn Morrow, Grants and Operations Manager[5]
Trong Tu Nguyen, Financial Accountant
Danielle Palermo, Administrative Assistant, Grants and Operations
Loretta Parker-Brown, Administrative Secretary
Catherine Piez, Systems and Fiscal Manager
Arona Primalani, Systems Intern[6]
Arnold J. Pryor, Facilities and Services Supervisor
Maxine F. Singer, President
John Strom, Administrative Support Assistant
Kris Sundback, Financial Manager
Vicki Tucker, Administrative Coordinator, Accounts Payable
Ernest Turner, Custodian (on call)
Susan Y. Vasquez, Assistant to the President
Yulonda White, Human Resources and Insurance Records Coordinator
Jacqueline J. Williams, Assistant to Manager, Human Resources and Insurance

CARNEGIE ACADEMY FOR SCIENCE EDUCATION (CASE)

Natalie Barnes, Mentor Teacher[7]
Michael J. Charles, CASE Intern[8]
Inés Cifuentes, CASE Program Coordinator
Risha J. Clark, Mentor Teacher[7]
Laura DeReitze, Early Childhood Education Specialist[9]
Linda Feinberg, Administrative
Theresa Gasaway, Mentor Teacher[7]
Patricia Goodnight, Mentor Teacher[7]
Margaret E. Jackson, Mentor Teacher[7]
Charles James, Director, Curriculum and Instruction, CASE, and Director, First Light
Mary Beth James, Early Childhood Coordinator[9]
Jacqueline Lee, Mentor Teacher[7]
Ronnie Lowenstein, Assessment Coordinator[10]
Avis McKinney-Thomas, Mentor Teacher[7]
Charles Mercer, Mentor Teacher[7]
Ollie Smith, Mentor Teacher[7]
Jerome Thornton, Mentor Teacher[11]
Sue White, Mathematics and Evaluations Coordinator[12]

* * *

[1] Members of the scientific departments are listed in the preceding sections.
[2] From September 6, 1994
[3] To November 4, 1994
[4] From November 22, 1994
[5] To July 27, 1994
[6] To December 9, 1994
[7] From May 1, 1995
[8] From April 18, 1995
[9] From February 1, 1995
[10] From May 1, 1994 to September 30, 1994
[11] From February 15, 1995
[12] From January 17, 1995

Publications and Special Events

Publications of the Institution

Sandage, Allan, and John Bedke, *The Carnegie Atlas of Galaxies,* Carnegie Institution of Washington publication 638, 2 volumes, viii + 750 pages, 354 illustration pages, December 1994.

Carnegie Institution of Washington Year Book 93, viii + 192 pages, 74 illustrations, December 1994.

Spectra: The Newsletter of the Carnegie Institution, issued in October 1994, April 1995, June 1995, special all-Carnegie symposium issue, March 1995.

Craig, Patricia, *Jumping Genes: The Scientific Legacy of Barbara McClintock*, Perspectives in Science booklet 6, 32 pages, 32 illustrations, December 1994, reprinted March 1995.

Carnegie Institution of Washington, informational booklet, 24 pages, 20 illustrations, September 1994.

Carnegie Evening 1995, 16 pages, 8 illustrations, May 1995.

Publications of the President and CASE Staff

Singer, Maxine, The responsibility of scientists to science education, *ASM News 60*, 458–459, 1994.

Cifuentes, Inés, Seismic moment and duration of recent large and great earthquakes, *J. Geophys. Res. 100*, 20303–20309, 1995.

Symposium

All-Carnegie Symposium, From Galaxies to Genes: Evolutionary Processes, Washington, D.C., October 8–9, 1994

Capital Science Lectures

Dean Hamer, Genes and Human Sexuality, October 18, 1994.

Thomas R. Cech, RNA Catalysis and the Origins of Life, November 15, 1994.

Eugene Shoemaker, When Comets Meet Planets, December 13, 1994.

Michael Robinson, The Joys of Biology: A Life of Research into Animal Behavior, January 31, 1995.

Roald Sagdeev, Chaos in Real Systems: The Limits of Predictability and Control, February 28, 1995.

Haresh C. Shah, Earthquake Risk Management—A Global Perspective, March 28, 1995.

Virgil L. Sharpton, Large Body Impacts in the History of Earth, April 18, 1995.

Wendy Freedman, Measuring the Expansion Rate of the Universe, May 16, 1995 (Carnegie Evening lecture).

Report of the Executive Committee

To the Trustees of the Carnegie Institution of Washington

In accordance with the provisions of the By-Laws, the Executive Committee submits this report to the Annual Meeting of the Board of Trustees.

During the fiscal year ending June 30, 1995, the Executive Committee has held four meetings. Accounts of these meetings have been or will be mailed to each Trustee.

A full statement of the finances and work of the Institution for the fiscal year ended June 30, 1994 appears in the Institution's *Year Book 93*, a copy of which has been sent to each Trustee. An estimate of the Institution's expenditures in the fiscal year ending June 30, 1996 appears in the budget recommended by the Committee for approval by the Board of Trustees.

The terms of the following members of the Board expire on May 6, 1994:

Philip H. Abelson
Robert G. Goelet
David Greenewalt
William R. Hearst III
John D. Macomber
Richard A. Meserve
Charles H. Townes
Thomas N. Urban
Sidney J. Weinberg, Jr.

In addition, the terms of the Chairman of the Board, all Committee Chairmen, and the following members of the Committees expire on May 5, 1995:

Finance Committee

David F. Swensen
Sidney J. Weinberg, Jr.

Employee Benefits Committee

William T. Coleman, Jr.
Edward E. David, Jr.
Sandra M. Faber

Executive Committee

Philip H. Abelson
John D. Macomber

Nominating Committee

Sidney J. Weinberg, Jr.

William I. M. Turner, Jr., *Chairman*

May 5, 1995

Abstract of Minutes

of the One Hundred and Second Meeting of the Board of Trustees

The Annual Meeting of the Board of Trustees was held in the Library of the Carnegie Observatories on Friday, May 5, 1995. The Meeting was called to order by the Chairman, Thomas N. Urban.

The following Trustees were present: Philip H. Abelson, John F. Crawford, Sandra M. Faber, Wallace Gary Ernst, Bruce W. Ferguson, William T. Golden, David Greenewalt, William R. Hearst III, Richard E. Heckert, Richard A. Meserve, William J. Rutter, David F. Swensen, Charles H. Townes, William I. M. Turner, Jr., Thomas N. Urban, and Sidney J. Weinberg, Jr. Also present were Caryl P. Haskins, Trustee Emeritus; Maxine F. Singer, President; Charles T. Prewitt, Director of the Geophysical Laboratory; Leonard Searle, Director of the Carnegie Observatories; Sean C. Solomon, Director of the Department of Terrestrial Magnetism; Allan C. Spradling, Director of the Department of Embryology; Christopher Somerville, Director of the Department of Plant Biology; John J. Lively, Director of Administration and Finance; Susanne Garvey, Director of Institutional and External Affairs; and Susan Y. Vasquez, Assistant Secretary.

The minutes of the One Hundred and First Meeting, held at the Department of Embryology on December 15–16, 1994, were approved.

Section 5.11 of the By-Laws was amended. The amended language is given in the By-Laws printed on pages 185–190 of this Year Book.

On recommendation of the Nominating Committee, the following were re-elected for terms ending in 1998: Philip H. Abelson, Robert G. Goelet, David Greenewalt, William R. Hearst III, John D. Macomber, Richard A. Meserve, Charles H. Townes, Thomas N. Urban, Sidney J. Weinberg, Jr.

Thomas N. Urban was elected Chairman of the Board of Trustees for a term ending in 1998.

The following were elected for one-year terms: William I. M. Turner, Jr., as Chairman of the Executive Committee; David F. Swensen, as Chairman of the Finance Committee; and William T.

Coleman, Jr., as Chairman of the Employee Benefits Committee. Sidney J. Weinberg, Jr., was appointed Chairman of the Nominating Committee for a one-year term.

The reports of the Executive Committee, the Finance Committee, the Employee Benefits Committee, and the Auditing Committee were accepted. On the recommendation of the latter, it was resolved that Price Waterhouse & Co. be appointed as public accountants for the fiscal year ending June 30, 1995.

The annual report of the President was received.

To provide for the operation of the Institution for the fiscal year ending June 30, 1996, and upon recommendation of the Executive Committee, the sum of $34,435,537 was appropriated.

Financial Statements

for the year ended June 30, 1995

Carnegie Institution of Washington
Ten-Year Financial Summary, 1986–1995

(All figures are thousands of dollars, fiscal years ended June 30)

	1995*	1994*	1993*	1992*	1991*	1990*	1989	1988	1987	1986
Revenues										
Investment earnings										
Interest and dividends	$ 8,422	$ 7,584	$ 8,479	$ 9,783	$ 11,422	$ 11,063	$ 12,062	$ 11,175	$ 10,629	$ 10,166
Realized net gain on investments	14,433	20,486	23,582	14,647	13,115	15,396	5,251	11,063	21,510	20,436
Less: investment service fees	(807)	(837)	(876)	(1,010)	(896)	(928)	(686)	(699)	(736)	(690)
Total investment earnings	22,048	27,233	31,185	23,420	23,641	25,531	16,627	21,539	31,403	29,912
Restricted grants, expended	13,932	11,062	9,145	7,946	6,927	5,999	6,059	5,924	4,673	5,595
Gifts and other	1,155	764	490	639	542	909	708	273	955	543
Total revenues	37,135	39,059	40,820	32,005	31,110	32,439	23,394	27,736	37,031	36,050
Capital contributions—equipment	2,202	946	1,410	954	675	572	...	...	...	...
Total revenues and capital contributions	39,337	40,005	42,230	32,959	31,785	33,011	23,394	27,736	37,031	36,050
Expenses										
Terrestrial Magnetism	4,657	3,932	3,181	3,195	3,155	3,227	2,656	2,837	2,595	2,873
Observatories	5,194	4,705	4,462	4,717	4,703	4,086	4,288	4,019	3,684	3,355
Geophysical Laboratory	5,471	4,409	4,343	4,024	3,808	3,271	2,932	2,989	2,511	2,399
Embryology	5,894	4,756	4,594	4,371	4,100	4,108	3,834	4,270	3,138	2,941
Plant Biology	4,450	3,843	3,265	2,699	2,781	2,351	2,155	1,846	1,985	1,828
Broad Branch Road campus	1,409	1,409	1,443	1,451	1,124	...	...	...	...	...
Research projects etc	779	586	290	138	267	164	112	99	83	88
Office of Administration	1,437	1,335	1,364	1,719	1,664	1,227	1,304	1,204	1,199	1,277
Office of publications	271	178	178	165	155	146	151	174	155	137
Professional fees, insurance, taxes	443	324	511	580	551	574	637	424	533	271
Retiree health insurance	425	393	376	391	406	355	274	252	213	211
Total expenses	30,430	25,870	24,007	23,450	22,714	19,509	18,343	18,114	16,096	15,380
Excess of revenues and capital contributions over expenses before capital changes	$ 8,907	$ 14,135	$ 18,223	$ 9,509	$ 9,071	$ 13,502	$ 5,051	$ 9,622	$ 20,935	$ 20,670
Net unrealized gain (loss) on investments	$ 20,989	$ (13,862)	$ 8,198	$ 7,452	$ (11,933)	$ 688	$ 11,268	$(17,967)	$ (3,756)	$ 25,295
Market value of investments	$334,084	$301,680	$274,461	$245,156	$225,639	$224,781	$222,582	$211,130	$227,734	$202,982

*Adjusted for the impact of Financial Accounting Standard No. 93, "Recognition of Depreciation by Not-for-Profit Organizations."

Contributions, Gifts, and Private Grants
for the Year Ended June 30, 1995

Anonymous
Philip H. Abelson
Abbott Laboratories Fund
Ahmanson Foundation
Jagannadham Akella
Gilles O. Allard
American Cancer Society
Bennett Archambault
Paul A. Armond, Jr.
Toshi Asada
Horace W. Babcock
Hubert L. Barnes
Manuel N. Bass
Walter and Shirley Berl
Giuseppe and L. Elizabeth Bertani
Jerry Brand
Bristol-Myers Squibb Foundation, Inc.
Jeanette and Walter Brown
Christopher Buchen
Gordon Burley
Kenneth D. Burrhus
Donald M. Burt
William Buscombe
Alice and Peter Buseck
Morris and Gwendolyn Cafritz Foundation
John A. R. Caldwell
Cancer Research Fund of Damon Runyon–Walter Winchell Foundation
Carnegie Corporation of New York
Carnegie Institution of Canada
Dana Carroll
James F. Case
Robert M. Cassie
Britton Chance
Jane Coffin Childs Memorial Fund for Medical Research
Matthias Chiquet
King-Chuen Chow
Robin Ciardullo
John and Annette Coleman
William T. Coleman, Jr.
Crestlea Foundation Inc.
John R. Cronin
Crystal Trust
Stephen M. Cutler
Sandro D'Odorico
Howard Clark Dalton
Igor B. Dawid
Vincent De Feo
John P. de Neufville
John and Ruth Doak
Bruce R. Doe
William N. Dove
Dudley Observatory
James and Alma Ebert
Jo Ann Eder
Electric Power Research Institute
Donald Elthon
W. Gary Ernst
John Ewel
Sandra and Andrew Faber
Bruce W. Ferguson
Andrew Fire
Dorothy Ruth Fischer
Michael and Helen Fleischer
Freeport McMoran Inc.
Domenico Gellera
M. Charles Gilbert
Kirsten and Oliver Gildersleeve, Jr.
Robert Glynn
Robert G. Goelet
Golden Family Foundation
Philip L. Graham Fund
Cecil and Ida Green Foundation
David Greenewalt
Richard and Irene Grill
Arthur Grossman
Helen M. Habermann
Pembroke J. Hart
Stanley R. Hart
Caryl and Edna Haskins
Robert M. Hazen
William R. Hearst III
Richard E. Heckert
Daniel Heinze
H. Lawrence Helfer
Alfred D. Hershey
William R. Hewlett
Hillsdale Fund, Inc.
Richard W. Higgins Foundation
Paul and Annetta Himmelfarb Foundation
Maximilian E. and Marion O. Hoffman Foundation
Satoshi Hoshina
Howard Hughes Medical Institute
William J. and Patricia Hume Fund
Kyoichi Ishizaka
Iwasaki Co.
Incorporated Research Institutions for Seismology
Institute for Advanced Study
International Human Frontier Science Program
Emilie Jaeger
George F. Jewett, Jr. 1965 Trust
Johnson & Johnson
W. M. Keck Foundation
David C. Koo
Olavi Kuovo
Kyocera Corporation
Steven W. L'Hernault

Contributions, Gifts, and Private Grants for the Year Ended June 30, 1995 (continued)

Otto C. and Ruth Landman
Kenneth G. Langone
Paul Latimer
Gerald D. Laubach Fund
Arthur and Faith W. LaVelle
Harold Lee
Life Sciences Research Foundation
Charles A. Little
Felix J. Lockman
Eric Long
Richard Lounsbery Foundation
Lucille P. Markey Charitable Trust
Mariah Associates, Inc.
Martek Biosciences Corporation
G. Harold and Leila Y. Mathers Charitable Foundation
Andrew W. Mellon Foundation
Mobil Foundation
Ambrose Monell Foundation
Monsanto Fund
John D. Macomber
Winston M. Manning
Marlow V. Marrs
Chester B. and Barbara C. Martin, Jr.
James M. Mattinson
Robert H. McCallister
Sheila McCormick
Steven L. McKnight
Andrew W. Mellon Foundation
John Merck Fund
Richard A. and Martha R. Meserve
Xenia S. and J. Irwin Miller Trust
Millipore Foundation
Ambrose Monell Foundation
Monsanto Company
Mary Lee Morrison
Gisela Mosig
Norio Murata
Jack E. Myers
Evelyn S. Nef
North Atlantic Treaty Organization
Norton Company
C. R. O'Dell
Kevin O'Hare
T. S. Okada
E. F. Osborn
Pew Scholars Program
Proctor & Gamble Company
David and Lucile Packard Foundation
Jeffrey D. Palmer
Neils M. Pedersen
Donald A. Pels
Charles J. Peterson
Pfizer Inc.
Lucy W. Pirtle
George Putnam
Raytheon Company
Philippe Reymond
J. R. Richards
Glenn C. Rosenquist
Vera C. Rubin
Alfred P. Sloan Foundation
Smithsonian Institution
Space Telescope Science Institute
Ruth N. Schairer
Paul Schechter
Maarten and Corrie Schmidt
Sara Lee Schupf
Eugenia A. and Robert C. Seamans, Jr.
Martin and Marilyn Seitz
Edwin and Virginia Shook
Dan and Maxine Singer
Elizabeth H. Smith
Allan Spradling
Ruth and Frank Stanton Fund
Bruce B. Stowe
Douglas K. Struck
Linda L. Stryker
Ziro Suzuki
David F. Swensen
Heinz Tiedemann
George R. Tilton
Scott B. Tollefsen
Charles H. Townes
U. S. Department of Agriculture
U. S. Geological Survey
U. S. Department of Energy
U. S. National Aeronautics and Space Administration
U. S. National Institutes of Health
U. S. National Science Foundation
U. S. Office of Naval Research
Thomas N. and Mary Urban
Larry N. Vanderhoef
Western Regional Center for the National Institute for Global Environmental Change
Wallace Genetic Foundation, Inc.
John L. Weinberg Family Fund
Sidney J. Weinberg, Jr., Foundation
James A. Weinman
Welfare Foundation, Inc.
Harry W. Wells
Wim Two, Inc.
Helen Hay Whitney Foundation
Rogier and Jeannie Windhorst
Evelyn M. Witkin
Woods Hole Oceanographic Institution
Kenzo Yagi
Masuru Yamaguchi
Yanofsky Family Rev. Trust

1301 K Street, N.W. 800W
Washington, DC 20005-3333

Telephone 202 414 1000

Price Waterhouse LLP

REPORT OF INDEPENDENT ACCOUNTANTS

September 29, 1995

To the Auditing Committee of the
Carnegie Institution of Washington

In our opinion, the accompanying statement of assets, liabilities and fund balances and the related statement of revenue, expenses and changes in fund balances present fairly, in all material respects, the financial position of the Carnegie Institution of Washington (the Institution) at June 30, 1995 and 1994, and the results of its operations and the changes in its fund balances for the years then ended in conformity with generally accepted accounting principles. These financial statements are the responsibility of the Institution's management; our responsibility is to express an opinion on these financial statements based on our audits. We conducted our audits of these statements in accordance with generally accepted auditing standards which require that we plan and perform the audit to obtain reasonable assurance about whether the financial statements are free of material misstatement. An audit includes examining, on a test basis, evidence supporting the amounts and disclosures in the financial statements, assessing the accounting principles used and significant estimates made by management, and evaluating the overall financial statement presentation. We believe that our audits provide a reasonable basis for the opinion expressed above.

Our audits were made for the purpose of forming an opinion on the basic financial statements taken as a whole. The supporting Schedules 1 through 4 are presented for purposes of additional analysis and are not a required part of the basic financial statements. Such information has been subjected to the auditing procedures applied in the audits of the basic financial statements, and in our opinion, is fairly stated in all material respects in relation to the basic financial statements taken as a whole.

Price Waterhouse LLP

Statement of Assets, Liabilities, and Fund Balances

June 30, 1995 and 1994

ASSETS	1995	1994
Current assets		
Cash	$ 219,561	$ 139,563
Grants receivable	2,347,053	2,416,831
Accounts receivable and other assets	974,495	1,628,662
Accrued interest and dividends receivable	763,971	1,154,145
Bond proceeds held by trustee*	19,647,483	28,002,077
Total current assets	23,952,563	33,341,278
Investments, at market#		
Temporary	32,215,153	15,889,760
Corporate stocks	138,288,287	129,544,822
Fixed income	70,658,982	68,060,889
Limited partnerships	73,060,996	59,954,993
Employee mortgage loans	213,084	227,846
Total investments	314,436,502	273,678,310
Property, plant, and equipment in service		
Buildings and building improvements	33,081,917	29,119,098
Scientific equipment	11,530,087	10,329,163
Telescopes	7,910,825	7,910,825
Administrative equipment	2,104,069	1,936,450
Land	1,086,742	1,086,742
Art and historical treasures	34,067	34,067
Less: accumulated depreciation	(18,507,759)	(16,547,169)
Property, plant, and equipment in service	37,239,948	33,869,176
Telescope under construction	15,028,562	7,016,424
Buildings under construction	1,146,575	2,617,161
Scientific equipment under construction	1,027,815	904,421
Total under construction	17,202,952	10,538,006
Net property, plant, and equipment	54,442,900	44,407,182
Total assets	$392,831,965	$351,426,770

LIABILITIES AND FUND BALANCES	1995	1994
Current Liabilities		
Accounts payable and accrued expenses	$ 3,838,243	$ 2,748,606
Deferred grant income	2,169,657	3,647,313
Broker payable	10,731,686	...
Total current liabilities	16,739,586	6,395,919
Bonds payable	34,927,206	34,918,382
Total liabilities	51,666,792	41,314,301
Fund balances	341,165,173	310,112,469
Total liabilities and fund balances	$392,831,965	$351,426,770

* Cost on June 30, 1995: $19,882,983. Cost on June 30, 1994: $28,608,237.

\# Cost on June 30, 1995: $269,027,804 (temporary $32,215,153, corporate stocks $107,551,620, fixed income $68,370,403, limited partnerships $60,677,544, employee mortgage loans $213,084). Cost on June 30, 1994: $248,883,120 (temporary $15,889,760, corporate stocks $107,850,484, fixed income $70,925,277, limited partnership $53,989,753, employee mortgage loans $227,846).

The accompanying notes are an integral part of these financial statements.

Statement of Revenue, Expenses, and Changes in Fund Balances for the Years Ended June 30, 1995 and 1994

	Year Ended June 30, 1995	Year Ended June 30, 1994
Revenue		
Investment earnings		
Interest and dividends	$ 8,422,071	$ 7,584,076
Realized gain on investments, net of losses and investment service fees	13,625,916	19,648,606
Net investment earnings	22,047,987	27,232,682
Grants		
Federal	8,698,010	7,105,200
Private	5,233,974	3,957,005
Gifts and other revenues	1,155,119	763,860
Total revenue	37,135,090	39,058,747
Capital contributions—for equipment purchases	2,202,049	946,083
Total revenue and capital contributions	39,337,139	40,004,830
Expenses		
Personnel and related	17,220,610	15,491,282
Equipment	4,668,391	3,623,032
General	8,541,471	6,755,623
Total expenses	30,430,472	25,869,937
Excess of revenue and capital contributions over expenses before capital changes	8,906,667	14,134,893
Capital changes		
Unrealized net gain (loss) on investments	20,988,794	(13,861,981)
Capital campaign—gifts	1,157,243	2,492,031
Total capital changes	22,146,037	(11,369,950)
Excess of revenue, capital contributions, and capital changes over expenses	31,052,704	2,764,943
Fund balances, beginning of year	310,112,469	307,347,526
Fund balances, end of year	$341,165,173	$310,112,469

The accompanying notes are an integral part of these financial statements.

Notes to The Financial Statements, June 30, 1995 and 1994

The Carnegie Institution of Washington (the Institution) is an institution for advanced research and training in the sciences. It carries out its work in five research centers: the Departments of Embryology, Plant Biology, and Terrestrial Magnetism, the Geophysical Laboratory, and the Observatories (astronomy). The Institution is exempt from federal income tax under Section 501(c)(3) of the Internal Revenue Code (the Code). Accordingly, no provision for income taxes is reflected in the accompanying financial statements. The Institution is also an educational institution within the meaning of Section 170(b)(1)(A)(ii) of the Code. The Internal Revenue Service has classified the Institution as other than a private foundation, as defined in Section 509(a) of the Code.

Note 1. Significant Accounting Policies

Basis of Accounting

The financial statements of the Institution are prepared on the accrual basis of accounting.

Investments

The Institution considers all highly liquid debt instruments purchased with original maturity dates of 90 days or less, excluding amounts that are classified as temporary investments, to be cash equivalents. Temporary investments reflect endowment and special fund investments in short-term instruments which are generally overnight investments. Investments are carried at market value. Realized gains from investments are included as additions to revenue while unrealized gains are included as capital changes in the Statement of Revenue, Expenses, and Changes in Fund Balances.

The Institution invests in shares of mutual funds; several of the mutual funds invest from time to time in derivative financial instruments. The Institution's exposure to loss is limited to the amount of its investment in the mutual fund shares.

Fair value of financial instruments

Financial instruments of the Institution include grants and accounts receivable, investments, accounts payable, and bonds payable. The fair value for investments and Series A bonds payable is based on quoted market price. The fair value of grants, accounts receivable, accounts payable, and Series B bonds payable is approximately equal to the carrying value.

Property, plant, and equipment

The Institution capitalizes expenditures for land, buildings and leasehold improvements, telescopes, scientific and administrative equipment, and projects in progress. Routine replacement, maintenance, and repairs are charged to expense.

Depreciation of the Institution's buildings, telescopes, and other equipment is computed on a straight-line basis using the following useful lives: buildings and telescopes, 50 years; buildings and leasehold improvements, 25 years or the remaining term of the lease; and scientific and administrative equipment, 5 years. Depreciation expense for the years ended June 30, 1995 and 1994 was $2,144,129 and $2,000,255, respectively.

Accounts payable

The accounts payable balance for the years ended June 30, 1995 and 1994 includes $1,087,965 and $787,851, respectively, of checks written and distributed but not yet drawn by the bank.

Contributions

Unrestricted gifts and bequests are recognized as income when they are received. Restricted gifts and bequests are recognized as income to the extent that expenditures are incurred for the intended purposes of the restricted gifts and bequests. Contributions for the purchase of fixed assets are recorded directly to fund balance until the assets are purchased, at which point revenue is recognized.

Note 2. Restricted Grants and Gifts

Restricted grants and gifts are funds received from foundations, individuals, and federal agencies in support of scientific research and educational programs. The Institution records revenues only to the extent that reimbursable expenditures are incurred. Accordingly, funds received in excess of reimbursable expenditures are recorded as deferred revenue, and expenditures in excess of reimbursements are recorded as accounts receivable. Reimbursement of indirect costs is based upon provisional rates which are subject to subsequent audit by the Institution's federal cognizant agency.

Note 3. Broker Payable

The Institution entered into certain investment transactions with trade dates prior to June 30, 1995. These transactions have been included in the investment balances. Since these amounts represent unsettled obligations at June 30, 1995, the net amount of $10,731,686 has also been presented as a liability until settlement occurs.

Note 4. Bonds Payable

On November 1, 1993 the Institution issued $17.5 million each of Series A and Series B California Educational Facilities Authority Revenue tax-exempt bonds. Bond proceeds are used to finance the Magellan project and the renovation of the facilities of the Observatories at Pasadena.

Series A bonds bear interest at 5.6% payable in arrears semiannually on each April 1 and October 1 and upon maturity on October 1, 2023. Series B bonds bear interest at variable money market rates in effect from time to time, up to a maximum of 12% over the applicable money market rate period of between one and 270 days and have a stated

Notes to the Financial Statements, June 30, 1995 and 1994 (continued)

maturity of October 1, 2023. At the end of each money market rate period, Series B bondholders are required to offer the bonds for repurchase at the applicable money market rate. If repurchased, the Series B bonds would be resold at the current applicable money market rate and for a new rate period.

The Institution is not required to repay the Series A and B bonds until the October 1, 2023 maturity date, and the Institution has the intent and the ability to effect the purchase and resale of the Series B bonds through a tender agent; therefore the bonds payable are classified as long term. Sinking fund redemptions begin in 2019 in installments for both series. The fair value of bonds payable at June 30, 1995 is approximately equal to $34,388,000. The fair value of Series A is based upon quoted market rates, and the fair value of Series B bonds is assumed to approximate carrying value at June 30, 1995, as the mandatory tender dates on which the bonds are repriced are generally less than three months before and after year end.

Note 5. Realized and Unrealized Gain and Loss on Investments

The realized and unrealized gain and loss on investments for the years ended June 30, 1995 and 1994 for the fixed income, equity, and limited partnership portions of the Institution's investment portfolio are as follows:

	Realized gain (loss)	Unrealized gain (loss)
Year ended June 30, 1995		
Fixed income	$ (1,495,000)	$ 5,528,000
Equity	15,173,000	9,042,000
Limited partnership	755,000	6,418,000
Total	$14,433,000	$20,988,000
Year ended June 30, 1994		
Fixed income	$ 2,417,000	$ (6,010,000)
Equity	$18,069,000	$ (7,852,000)
Total	$20,486,000	$(13,862,000)

Note 6. Employee Benefit Plans

Retirement Plan

The Institution has a noncontributory, defined contribution, money-purchase retirement plan in which all United States personnel are eligible to participate. After one year's participation, an individual's benefits are fully vested. The Plan has been funded through individually owned annuities issued by Teachers' Insurance and Annuity Association (TIAA) and College Retirement Equities Fund (CREF). There are no unfunded past service costs. The total contributions made by the Institution were $1,677,169 and $1,532,862 in 1995 and 1994, respectively.

Post-retirement benefits

The Institution provides health insurance for retired employees. Most of the Institution's United States employees become eligible for these benefits at retirement. The cost of retiree health insurance benefits is currently being recognized in expense as costs are incurred. For the years ended June 30, 1995 and 1994, these costs were $425,165 and $393,044, respectively.

The provisions of Statement of Financial Accounting Standards No. 106, "Employer's Accounting for Post Retirement Benefits Other Than Pensions," have not yet been adopted by the Institution. This Statement requires that the cost of such benefits be estimated in advance and recognized over the period of service of the employee. The Institution will be required to adopt the provisions of this standard for the fiscal year ending June 30, 1996. The actuarially determined estimate of the transition obligation on an immediate recognition basis on July 1, 1995 is approximately $10,727,000.

Note 7. Adoption of Statements of Financial Accounting Standards 116 and 117

The Institution intends to adopt the Statement of Financial Accounting Standards (SFAS) No. 116, "Accounting for Contributions Received and Contributions Made," and No. 117, "Financial Statements of Not-for-Profit Organizations," when required, effective July 1, 1995. The intent of these new standards is to standardize and simplify financial reporting by not-for-profit organizations. SFAS 116 requires that unconditional pledges be recognized at their fair value when the pledge is made, conditional pledges be recognized when the underlying condition is met, and donated services be recognized in revenue and expense if certain criteria are met. SFAS 117 standardizes the financial statement presentation of not-for-profit organizations.

Schedule 1

Schedule of Expenses by Department

for the Years Ended June 30, 1995 and 1994

	1995				1994
		Restricted Grants			
	Endowment and Special	Federal	Private	Total Expenses	Total Expenses
Education and scientific research expenses					
Terrestrial Magnetism	$ 2,266,760	$ 2,124,132	$ 265,693	$ 4,656,585	$ 3,932,324
Observatories	3,938,016	471,463	784,996	5,194,475	4,705,205
Geophysical Laboratory	2,435,631	1,453,749	1,581,912	5,471,292	4,408,743
Embryology	1,726,964	2,258,891	1,908,103	5,893,958	4,756,307
Plant Biology	2,148,150	1,841,596	459,866	4,449,612	3,843,353
Broad Branch Road campus	1,407,100	...	1,990	1,409,090	1,408,907
Other activities	...	548,179	231,414	779,593	585,677
Total	13,922,621	8,698,010	5,233,974	27,854,605	23,640,516
Administrative and general expenses					
Office of Administration	1,436,761	...	...	1,436,761	1,334,993
Office of publications	270,841	...	...	270,841	177,506
Professional fees, insurance, taxes	443,100	...	...	443,100	323,878
Retiree health insurance	425,165	...	...	425,165	393,044
Total	2,575,867	...	...	2,575,867	2,229,421
Total expenses, 1995	$16,498,488	$8,698,010	$5,233,974	$30,430,472	
Total expenses, 1994	$14,812,732	$7,105,200	$3,952,005		$25,869,937

CHANGES IN FUND BALANCES FOR THE YEAR ENDED JUNE 30, 1995

	Balance July 1, 1994	Investment, Grant, and Other Income	Endowment and Special Gifts	Total Net Capital Gains	Expenses	Other	Balance June 30, 1995
Restricted endowment funds							
Andrew Carnegie	$225,225,299	...	...	$28,822,650	...	...	$254,047,949
Golden	1,599,526	...	...	204,694	...	...	1,804,220
Anonymous	6,134,477	...	...	785,045	...	...	6,919,522
Mellon matching	3,485,410	...	$ 254,100	446,037	...	...	4,185,547
Anonymous matching	3,918,715	...	...	501,488	...	...	4,420,203
Unrestricted capital funds							
Carnegie Corporation and other	(6,896,320)	...	...	606,161	...	$(15,592,921)	(21,883,080)*
Carnegie futures	2,875,242	...	192,672	367,952	...	(59,149)	3,376,717
Bush bequest	503,540	...	...	64,439	...	...	567,979
Working capital fund	...	$ 7,556,034	...	...	$(13,736,193)	6,180,159	...
Restricted grants	...	13,931,984	...	...	(13,931,984)	...	...
Special funds							
Astronomy	4,485,055	125,543	20,000	573,964	(270,000)	...	4,934,562
Bowen	1,337,862	37,449	...	171,210	(43,000)	...	1,503,521
Bush	98,397	2,754	...	12,592	(12,000)	...	101,743
Capital campaign	15,611,662	421,665	1,067,931	1,927,793	...	(565,036)	18,464,015
Colburn	1,136,836	31,822	...	145,484	(42,000)	...	1,272,142
Forbush	73,896	2,068	...	9,457	(2,000)	...	83,421
Ferguson	23,192	649	1,125	2,968	(24,625)	...	3,309
Hale	47,034	1,317	...	6,018	(2,000)	...	52,369
Harkavy	48,540	1,359	...	6,212	(2,000)	...	54,111
Lundmark	178,737	5,003	...	22,873	(7,000)	...	199,613
McClintock	707,666	19,808	43,187	90,561	(32,276)	...	828,946
Morganroth	134,989	3,779	...	17,275	(5,000)	...	151,043
Moseley astronomy	447,332	12,521	...	57,246	(15,000)	...	502,099
Moseley	72,913	2,041	...	9,331	...	...	84,285
Pogo	255,139	7,142	...	32,651	...	...	294,932
Roberts	229,382	6,421	...	29,355	(7,280)	...	257,878
Special instrumentation	630,412	17,646	...	80,675	(40,000)	...	688,733
Special opportunities	410,648	11,495	...	52,552	(20,000)	...	454,695
Wood	2,802,934	78,458	...	358,699	(88,985)	...	3,151,106
Other	126,772	3,549	...	16,223	(5,000)	59,149	200,693
Endowment and similar	265,705,287	22,280,507	1,579,015	35,421,605	(28,286,343)	(9,977,798)	286,722,273
Plant fund—in service	33,869,176	...	971,234	...	(2,144,129)	4,543,667	37,239,948
Assets under construction	10,538,006	...	1, 230,815	...	...	$ 5,434,131	17,202,952
Total	$310,112,469	$22,280,507	$3,781,064	$35,421,605	$(30,430,472)	...	$341,165,173

* Balance does not include proceeds from bond offering.

Schedule 3
1 of 2

Restricted Grants and Gifts for the Year Ended June 30, 1995

	Balance July 1, 1994	New Restricted Grants/Gifts	Expenses	Balance June 30, 1995
Federal grants and contracts				
Department of Agriculture	$ 226,143	$ 100,000	$ 84,633	$ 241,510
Department of Energy	614,091	539,569	808,666	344,994
Department of the Interior	16,310	...	...	16,310
Geological Survey	...	90,000	9,295	80,705
National Aeronautics and Space Administration	1,942,866	1,324,643	1,461,320	1,806,189
National Science Foundation	2,707,276	4,625,458	4,048,711	3,284,023
Office of Naval Research	120,142	150,000	93,724	176,418
Public Health Service	1,644,934	1,709,413	2,191,661	1,162,686
Total Federal grants and contracts	7,271,762	8,539,083	8,698,010	7,112,835
Private grants				
Ahmanson Foundation	250,000	100,000	257,289	92,711
Rita Allen Foundation	32,355	...	29,952	2,403
American Association for the Advancement of Science	3,000	...	...	3,000
American Astronomical Society	5,388	...	1,734	3,654
American Cancer Society	517,337	176,663	169,025	524,975
American Society for Microbiology	3,307	...	...	3,307
University of Arizona	...	24,000	8,000	16,000
California Institute of Technology	63,308	71,781	21,884	113,205
University of California, Santa Cruz	25,802	...	...	25,802
Capital Science Lecture Series	69,764	12,000	33,650	48,114
Carnegie Institution of Canada	...	7,260	...	7,260
Carnegie Senior Fellow	106,106	...	24,779	81,327
Jane Coffin Childs Memorial Fund for Medical Research	42,981	81,065	55,500	68,546
Chilean Fellowship	5,500	...	...	5,500
Crabtree & Jemison, Inc.	...	97,840	18,625	79,215
Donnay Fund	6,018	...	500	5,518
Dudley Observatory	8,203	...	6,446	1,757
Duke University	39	...	...	39
David Dunlap Observatory	10,354	...	2,961	7,393
Embryology Fund	112,500	247,887	326,478	33,909
First Light/Academy for Science Education	1,222	220,010	71,267	149,965
Flintridge Foundation	78,257	...	75,413	2,844
Geophysical Fund	7,550	55,640	48,929	14,261
Philip Graham Fund	...	100,000	...	100,000
Robert Hazen	52,509	30,000	35,096	47,413
Howard Hughes Medical Institute	29,051	233,500	189,288	73,263
Institute for Advanced Study	38,099	47,061	32,222	52,938
International Human Frontier Science Program	44,667	22,000	6,640	60,027
Johns Hopkins University	134,384	...	...	134,384
Johnson & Johnson	500,000	...	...	500,000
W. M. Keck Foundation	733,130	28,582	732,412	29,300
Kresge Foundation	14,346	...	4,056	10,290
Laubach Foundation/Community Trust	...	25,000	...	25,000
Lead Trust	1,021,812	...	535,599	486,213
Leukemia Society of America	108,268	...	...	108,268
Life Sciences Research Foundation	9,499	33,900	25,501	17,898
John D. & Catherine T. MacArthur Foundation	9,897	...	...	9,897
McKnight Endowment Fund for Neuroscience	39,999	...	39,999	...

(continued)

Schedule 3
2 of 2

RESTRICTED GRANTS AND GIFTS
(Continued)

	Balance July 1, 1994	New Restricted Grants/Gifts	Expenses	Balance June 30, 1995
Lucille P. Markey Charitable Trust	338,459	...	95,793	242,666
Martek Biosciences Corporation	8,481	24,000	16,843	15,638
G. Harold and Leila Y. Mathers Charitable Foundation	538,041	...	168,917	369,124
Andrew W. Mellon Foundation	324,712	10,166	126,777	208,101
John Merck Fund	329,563	...	153,479	176,084
Michigan State University	...	61,493	61,493	...
Mobil Oil Corporation	13,446	...	13,242	204
Ambrose Monell Foundation	185,320	150,000	200,814	134,506
Monsanto Company	20,000	...	...	20,000
North Atlantic Treaty Organization	...	5,649	1,979	3,670
Norton Company	33,529	65,000	68,676	29,853
Observatories Fund	9,296	5,250	7,467	7,079
People's Republic of China	4,285	...	...	4,285
Plant Biology Fund	90	4,100	837	3,353
Polish telescope	...	7,000	7,000	...
Proctor & Gamble Co.	59,407	...	5,153	54,254
Richard B. T. Roberts Memorial Fund	1,650	...	...	1,650
John D. Rockefeller Foundation	3,734	...	...	3,734
Vera C. Rubin Fund	7,213	5,000	4,785	7,428
Damon Runyon–Walter Winchell Cancer Research Fund	93,527	94,000	8,250	179,277
Alfred P. Sloan Foundation	25,000	...	25,000	...
Scientific Alliance for South America	...	27,500	4,706	22,794
Space Telescope Science Institute	529,086	407,252	459,517	476,821
State University of New York at Stony Brook	517,970	800,000	981,326	336,644
Terrestrial Magnetism Fund	...	1,200	...	1,200
Weizmann Institute	1,042	...	...	1,042
Western Regional Center of the National Institute for Global Environmental Change	8,505	...	...	8,505
Helen Hay Whitney Foundation	155,405	...	55,469	99,936
Woods Hole Oceanographic Institution	21,206	...	13,206	8,000
Total private grants and contracts	7,313,619	3,281,799	5,233,974	5,361,444
Total restricted grants and contracts	14,585,381	$11,820,882	$13,931,984	12,474,279
Less cash not yet earned or received from grants and contracts	(10,938,068)			(10,304,622)
Deferred income	$3,647,313			$2,169,657

Schedule 4

Schedule of Expenses

for the Years Ended June 30, 1995 and 1994

	1995			1994
	Endowment and Special	Restricted Grants	Total Expenses	Total Expenses
Salaries, fringe benefits, and payroll taxes				
Salaries	$ 8,964,315	$ 3,068,821	$12,033,136	$10,937,840
Fringe benefits and payroll taxes	2,450,261	818,451	3,268,712	2,971,713
Retiree health insurance	425,165	...	425,165	393,044
Total	11,839,741	3,887,272	15,727,013	14,302,597
Fellowship grants and awards	735,722	948,713	1,684,435	1,229,261
Equipment	2,167,194	2,501,197	4,668,391	3,623,032
General expenses				
Educational and research supplies	521,422	1,479,123	2,000,545	1,660,810
Contract services	217,943	1,422,372	1,640,315	813,663
Building maintenance and repairs	343,326	2,534	345,860	442,958
Utilities	987,517	595	988,112	939,180
Administrative	710,803	120,782	831,585	567,218
Computer services	65,934	...	65,934	72,418
Travel and meetings	522,327	542,144	1,064,471	873,773
General insurance	203,769	...	203,769	185,918
Scientific publications	26,958	58,283	85,241	66,075
Professional and consulting fees	228,770	186,647	415,417	269,069
Commissary	44,199	...	44,199	42,444
Shop	58,886	...	58,886	78,195
Telephone	192,275	822	193,097	235,026
Postage and shipping	150,301	10,405	160,706	156,578
Books and subscriptions	198,896	3,503	202,399	193,659
Contributions and miscellaneous	145,049	26,316	171,365	220,544
Total general expenses	4,618,375	3,853,526	8,471,901	6,817,528
Indirect costs—grants	(2,741,276)	2,741,276	...	...
Indirect costs capitalized on scientific construction projects	(121,268)	...	(121,268)	(102,481)
Total expenses	$16,498,488	$13,931,984	$30,430,472	$25,869,937

Articles of Incorporation

Fifty-eighth Congress of the United States of America;

At the Second Session,

Begun and held at the City of Washington on Monday, the seventh day of December, one thousand nine hundred and three.

AN ACT

To incorporate the Carnegie Institution of Washington.

Be it enacted by the Senate and House of Representatives of the United States of America in Congress assembled, That the persons following, being persons who are now trustees of the Carnegie Institution, namely, Alexander Agassiz, John S. Billings, John L. Cadwalader, Cleveland H. Dodge, William N. Frew, Lyman J. Gage, Daniel C. Gilman, John Hay, Henry L. Higginson, William Wirt Howe, Charles L. Hutchinson, Samuel P. Langley, William Lindsay, Seth Low, Wayne MacVeagh, Darius O. Mills, S. Weir Mitchell, William W. Morrow, Ethan A. Hitchcock, Elihu Root, John C. Spooner, Andrew D. White, Charles D. Walcott, Carroll D. Wright, their associates and successors, duly chosen, are hereby incorporated and declared to be a body corporate by the name of the Carnegie Institution of Washington and by that name shall be known and have perpetual succession, with the powers, limitations, and restrictions herein contained.

SEC. 2. That the objects of the corporation shall be to encourage, in the broadest and most liberal manner, investigation, research, and discovery, and the application of knowledge to the improvement of mankind; and in particular—

(a) To conduct, endow, and assist investigation in any department of science, literature, or art, and to this end to cooperate with governments, universities, colleges, technical schools, learned societies, and individuals.

(b) To appoint committees of experts to direct special lines of research.

(c) To publish and distribute documents.

(d) To conduct lectures, hold meetings, and acquire and maintain a library.

(e) To purchase such property, real or personal, and construct such building or buildings as may be necessary to carry on the work of the corporation.

(f) In general, to do and perform all things necessary to promote the objects of the institution, with full power, however, to the trustees hereinafter appointed and their successors from time to time to modify the conditions and regulations under which the work shall be carried on, so as to secure the application of the funds in the manner best adapted to the conditions of the time, provided that the objects of the corporation shall at all times be among the foregoing or kindred thereto.

Sec. 3. That the direction and management of the affairs of the corporation and the control and disposal of its property and funds shall be vested in a board of trustees, twenty-two in number, to be composed of the following individuals: Alexander Agassiz, John S. Billings, John L. Cadwalader, Cleveland H. Dodge, William N. Frew, Lyman J. Gage, Daniel C. Gilman, John Hay, Henry L. Higginson, William Wirt Howe, Charles L. Hutchinson, Samuel P. Langley, William Lindsay, Seth Low, Wayne MacVeagh, Darius O. Mills, S. Weir Mitchell, William W. Morrow, Ethan A. Hitchcock, Elihu Root, John C. Spooner, Andrew D. White, Charles D. Walcott, Carroll D. Wright, who shall constitute the first board of trustees. The board of trustees shall have power from time to time to increase its membership to not more than twenty-seven members. Vacancies occasioned by death, resignation, or otherwise shall be filled by the remaining trustees in such manner as the by-laws shall prescribe; and the persons so elected shall thereupon become trustees and also members of the said corporation. The principal place of business of the said corporation shall be the city of Washington, in the District of Columbia.

Sec. 4. That such board of trustees shall be entitled to take, hold and administer the securities, funds, and property so transferred by said Andrew Carnegie to the trustees of the Carnegie Institution and such other funds or property as may at any time be given, devised, or bequeathed to them, or to such corporation, for the purposes of the trust; and with full power from time to time to adopt a common seal, to appoint such officers, members of the board of trustees or otherwise, and such employees as may be deemed necessary in carrying on the business of the corporation, at such salaries or with such remuneration as they may deem proper; and with full power to adopt by-laws from time to time and such rules or regulations as may be necessary to secure the safe and convenient transaction of the business of the corporation; and with full power and discretion to deal with and expend the income of the corporation in such manner as in their judgment will best promote the objects herein set forth and in general to have and use all powers and authority necessary to promote such objects and carry out the purposes of the donor. The said trustees shall have further power from time

to time to hold as investments the securities hereinabove referred to so transferred by Andrew Carnegie, and any property which has been or may be transferred to them or such corporation by Andrew Carnegie or by any other person, persons, or corporation, and to invest any sums or amounts from time to time in such securities and in such form and manner as are permitted to trustees or to charitable or literary corporations for investment, according to the laws of the States of New York, Pennsylvania, or Massachusetts, or in such securities as are authorized for investment by the said deed of trust so executed by Andrew Carnegie, or by any deed of gift or last will and testament to be hereafter made or executed.

Sec. 5. That the said corporation may take and hold any additional donations, grants, devises, or bequests which may be made in further support of the purposes of the said corporation, and may include in the expenses thereof the personal expenses which the trustees may incur in attending meetings or otherwise in carrying out the business of the trust, but the services of the trustees as such shall be gratuitous.

Sec. 6. That as soon as may be possible after the passage of this Act a meeting of the trustees hereinbefore named shall be called by Daniel C. Gilman, John S. Billings, Charles D. Walcott, S. Weir Mitchell, John Hay, Elihu Root, and Carroll D. Wright, or any four of them, at the city of Washington, in the District of Columbia, by notice served in person or by mail addressed to each trustee at his place of residence; and the said trustees, or a majority thereof, being assembled, shall organize and proceed to adopt by-laws, to elect officers and appoint committees, and generally to organize the said corporation; and said trustees herein named, on behalf of the corporation hereby incorporated, shall thereupon receive, take over, and enter into possession, custody, and management of all property, real or personal, of the corporation heretofore known as the Carnegie Institution, incorporated, as hereinbefore set forth under "An Act to establish a Code of Law for the District of Columbia, January fourth, nineteen hundred and two," and to all its rights, contracts, claims, and property of any kind or nature; and the several officers of such corporation, or any other person having charge of any of the securities, funds, real or personal, books or property thereof, shall, on demand, deliver the same to the said trustees appointed by this Act or to the persons appointed by them to receive the same; and the trustees of the existing corporation and the trustees herein named shall and may take such other steps as shall be necessary to carry out the purposes of this Act.

Sec. 7. That the rights of the creditors of the said existing corporation known as the Carnegie Institution shall not in any manner be impaired by the

passage of this Act, or the transfer of the property hereinbefore mentioned, nor shall any liability or obligation for the payment of any sums due or to become due, or any claim or demand, in any manner or for any cause existing against the said existing corporation, be released or impaired; but such corporation hereby incorporated is declared to succeed to the obligations and liabilities and to be held liable to pay and discharge all of the debts, liabilities, and contracts of the said corporation so existing to the same effect as if such new corporation had itself incurred the obligation or liability to pay such debt or damages, and no such action or proceeding before any court or tribunal shall be deemed to have abated or been discontinued by reason of the passage of this Act.

Sec. 8. That Congress may from time to time alter, repeal, or modify this Act of incorporation, but no contract or individual right made or acquired shall thereby be divested or impaired.

Sec. 9. That this Act shall take effect immediately.

J G Cannon

Speaker of the House of Representatives.

Wm P Frye

President of the Senate pro tempore.

Approved.
April 28. 1904.
Theodore Roosevelt

By-Laws of the Institution

Adopted December 13, 1904. Amended December 13, 1910, December 13, 1912, December 10, 1937, December 15, 1939, December 13, 1940, December 18, 1942, December 12, 1947, December 10, 1954, October 24, 1957, May 8, 1959, May 13, 1960, May 10, 1963, May 15, 1964, March 6, 1967, May 3, 1968, May 14, 1971, August 31, 1972, May 9, 1974, April 30, 1976, May 1, 1981, May 7, 1982, May 3, 1985, May 9, 1986, May 15, 1987, May 6, 1988, May 5, 1989, May 10, 1991, May 6, 1994, and May 5, 1995.

ARTICLE I

The Trustees

1.1. The Board of Trustees shall consist of up to twenty-seven members as determined from time to time by the Board.

1.2. The Board of Trustees shall be divided into three classes approximately equal in number. The terms of the Trustees shall be such that those of the members of one class expire at the conclusion of each annual meeting of the Board. At each annual meeting of the Board vacancies resulting from the expiration of Trustees' terms shall be filled by their re-election or election of their successors. Trustees so re-elected or elected shall serve for terms of three years expiring at the conclusion of the annual meeting of the Board in the third year after their election. A vacancy resulting from the resignation, death, or incapacity of a Trustee before the expiration of his or her term may be filled by election of a successor at or between annual meetings. A person elected to succeed a Trustee before the expiration of his or her term shall serve for the remainder of that term unless the Board determines that assignment to a class other than the predecessor's is appropriate. There shall be no limit on the number of terms for which a Trustee may serve, and a Trustee shall be eligible for immediate re-election upon expiration of his or her term.

1.3. No Trustee shall receive any compensation for his or her services as such.

1.4. Trustees shall be elected by vote of two-thirds of the Trustees present at a meeting of the Board of Trustees at which a quorum is present or without a meeting by written action of all of the Trustees pursuant to Section 4.6.

1.5. If, at any time during an emergency period, there be no surviving Trustee capable of acting, the President, the Director of each existing Department, or such of them as shall then be surviving and capable of acting, shall constitute a Board of Trustees *pro tem*, with full powers under the provisions of the Articles of Incorporation and these By-Laws. Should neither the President nor any such Director be capable of acting, the senior surviving Staff Member of each existing Department shall be a Trustee *pro tem*, with full powers of a Trustee under the Articles of Incorporation and these By-Laws. It shall be incumbent on the Trustees *pro tem* to reconstitute the Board with permanent members within a reasonable time after the emergency has passed, at which time the Trustees *pro tem* shall cease to hold office. A list of Staff Member seniority, as designated annually by the President, shall be kept in the Institution's records.

1.6. A Trustee who resigns after having served at least six years and having reached age seventy shall be eligible for designation by the Board of Trustees as a Trustee Emeritus. A Trustee Emeritus shall be entitled to attend meetings of the Board but shall have no vote and shall not be counted for purposes of ascertaining the presence of a quorum. A Trustee Emeritus may be invited to serve in an advisory capacity on any committee of the Board except the Executive Committee.

ARTICLE II

Officers of the Board

2.1. The officers of the Board shall be a Chairman of the Board, a Vice-Chairman, and a Secretary, who shall be elected by the Trustees, from the members of the Board, by ballot to serve for a term of three years. All vacancies shall be filled by the Board for the unexpired term; provided, however, that the Executive Committee shall have power to fill a vacancy in the office of Secretary to serve until the next meeting of the Board of Trustees.

2.2. The Chairman shall preside at all meetings and shall have the usual powers of a presiding officer.

2.3. The Vice-Chairman, in the absence or disability of the Chairman, shall perform the duties of the Chairman.

2.4. The Secretary shall issue notices of meetings of the Board, record its transactions, and conduct that part of the correspondence relating to the Board and to his or her duties.

ARTICLE III

Executive Administration

3.1. There shall be a President who shall be elected by ballot by, and hold office during the pleasure of, the Board, who shall be the chief executive officer of the Institution. The President, subject to the control of the Board and the Executive Committee, shall have general charge of all matters of administration and supervision of all arrangements for research and other work undertaken by the Institution or with its funds. He or she shall prepare and submit to the Board of Trustees and to the Executive Committee plans and suggestions for the work of the Institution, shall conduct its general correspondence and the correspondence with applicants for grants and with the special advisors of the Committee, and shall present his or her recommendations in each case to the Executive Committee for decision. All proposals and requests for grants shall be referred to the President for consideration and report. He or she shall have power to remove, appoint, and, within the scope of funds made available by the Trustees, provide for compensation of subordinate employees and to fix the compensation of such employees with the limits of a maximum rate of compensation to be established from time to time by the Executive Committee. The President shall be *ex officio* a member of the Executive Committee and the Finance Committee.

3.2. The President shall be the legal custodian of the seal and of all property of the Institution whose custody is not otherwise provided for. He or she shall sign and execute on behalf of the corporation all contracts and instruments necessary in authorized administrative and research matters and affix the corporate seal thereto when necessary, and may delegate the performance of such acts and other administrative duties in his or her absence to other officers. He or she may execute all other contracts, deeds, and instruments on behalf of the corporation and affix the seal thereto when expressly authorized by the Board of Trustees or Executive Committee. He or she may, within the limits of his or her own authorization, delegate to other officers authority to act as custodian of and affix the corporate seal. He or she shall be responsible for the expenditure and disbursement of all funds of the Institution in accordance with the directions of the Board and of the Executive Committee, and shall keep accurate accounts of all receipts and disbursements. He or she shall, with the assistance of the Directors of

the Departments, prepare for presentation to the Trustees and for publication an annual report on the activities of the Institution.

3.3. The President shall attend all meetings of the Board of Trustees.

3.4. The corporation shall have such other officers as may be appointed by the Executive Committee, having such duties and powers as may be specified by the Executive Committee or by the President under authority from the Executive Committee.

3.5. The President shall retire from office at the end of the fiscal year in which he or she becomes sixty-five years of age, except as retirement may be deferred by the Board of Trustees for one or more periods of up to three years each. The corporate officers appointed by the Executive Committee shall retire, and the Directors of Departments shall retire as Directors, at the end of the fiscal year in which they become sixty-five years of age, except as otherwise required by law or as retirement may be deferred by the Executive Committee.

ARTICLE IV

Meetings and Voting

4.1. The annual meeting of the Board of Trustees shall be held in the City of Washington, in the District of Columbia, in May of each year on a date fixed by the Executive Committee, or at such other time or such other place as may be designated by the Executive Committee, or if not so designated prior to May 1 of such year, by the Chairman of the Board of Trustees, or if he or she is absent or is unable or refuses to act, by any Trustee with the written consent of the majority of the Trustees then holding office.

4.2. Special meetings of the Board of Trustees may be called, and the time and place of meeting designated, by the Chairman, or by the Executive Committee, or by any Trustee with the written consent of the majority of the Trustees then holding office. Upon the written request of seven members of the Board, the Chairman shall call a special meeting.

4.3. Notices of meetings shall be given ten days prior to the date thereof. Notice may be given to any Trustee personally, or by mail or by telegram sent to the usual address of such Trustee. Notices of adjourned meetings need not be given except when the adjournment is for ten days or more.

4.4. The presence of a majority of the Trustees holding office shall constitute a quorum for the transaction of business at any meeting. An act of the majority of the Trustees present at a meeting at which a quorum is present shall be the act of the Board except as otherwise provided in these By-Laws. If, at a duly called meeting, less than a quorum is present, a majority of those present may adjourn the meeting from time to time until a quorum is present. Trustees present at a duly called or held meeting at which a quorum is present may continue to do business until adjournment notwithstanding the withdrawal of enough Trustees to leave less than a quorum.

4.5. The transactions of any meeting, however called and noticed, shall be as valid as though carried out at a meeting duly held after regular call and notice, if a quorum is present and if, either before or after the meeting, each of the Trustees not present in person signs a written waiver of notice, or consent to the holding of such meeting, or approval of the minutes thereof. All such waivers, consents, or approvals shall be filed with the corporate records or made a part of the minutes of the meeting.

4.6. Any action which, under law or these By-Laws, is authorized to be taken at a meeting of the Board of Trustees or any of the Standing Committees may be taken without a meeting if authorized in a document or documents in writing signed by all

the Trustees, or all the members of the Committee, as the case may be, then holding office and filed with the Secretary.

4.7. During any emergency period the term "Trustees holding office" shall, for purposes of this Article, mean the surviving members of the Board who have not been rendered incapable of acting for any reason including difficulty of transportation to a place of meeting or of communication with other surviving members of the Board.

ARTICLE V

Committees

5.1. There shall be the following Standing Committees, *viz.* an Executive Committee, a Finance Committee, an Auditing Committee, a Nominating Committee, and an Employee Benefits Committee.

5.2. All vacancies in the Standing Committees shall be filled by the Board of Trustees at the next annual meeting of the Board and may be filled at a special meeting of the Board. A vacancy in the Executive Committee and, upon request of the remaining members of any other Standing Committee, a vacancy in such other Committee may be filled by the Executive Committee by temporary appointment to serve until the next meeting of the Board.

5.3. The terms of all officers and of all members of Committees, as provided for herein, shall continue until their successors are elected or appointed. The term of any member of a Committee shall terminate upon termination of his or her service as a Trustee.

Executive Committee

5.4. The Executive Committee shall consist of the Chairman, Vice-Chairman, and Secretary of the Board of Trustees, the President of the Institution *ex officio*, and, in addition, not less than five or more than eight Trustees to be elected by the Board by ballot for a term of three years, who shall be eligible for re-election. Any member elected to fill a vacancy shall serve for the remainder of his or her predecessor's term. The presence of four members of the Committee shall constitute a quorum for the transaction of business at any meeting.

5.5. The Executive Committee shall, when the Board is not in session and has not given specific directions, have general control of the administration of the affairs of the corporation and general supervision of all arrangements for administration, research, and other matters undertaken or promoted by the Institution. It shall also submit to the Board of Trustees a printed or typewritten report of each of its meetings, and at the annual meeting shall submit to the Board a report for publication.

5.6. The Executive Committee shall have power to authorize the purchase, sale, exchange or transfer of real estate.

Finance Committee

5.7. The Finance Committee shall consist of not less than five and not more than six Trustees to be elected by the Board by ballot for a term of three years, who shall be eligible for re-election, and the President of the Institution *ex officio*. The presence of three members of the Committee shall constitute a quorum for the transaction of business at any meeting.

5.8. The Finance Committee shall have custody of the securities of the Institution and

general charge of its investments and invested funds and shall care for and dispose of the same subject to the directions of the Board of Trustees. It shall have power to authorize the purchase, sale, exchange, or transfer of securities and to delegate this power. For any retirement or other benefit plan for the staff members and employees of the Institution, it shall be responsible for supervision of matters relating to investments, appointment or removal of any investment manager or advisor, reviewing the financial status and arrangements, and appointment or removal of any plan trustee or insurance carrier. It shall consider and recommend to the Board from time to time such measures as in its opinion will promote the financial interests of the Institution and improve the management of investments under any retirement or other benefit plan. The Committee shall make a report at the annual meeting of the Board.

Auditing Committee

5.9. The Auditing Committee shall consist of three members to be elected by the Board of Trustees by ballot for a term of three years.

5.10. Before each annual meeting of the Board of Trustees, the Auditing Committee shall cause the accounts of the Institution for the preceding fiscal year to be audited by public accountants. The accountants shall report to the Committee, and the Committee shall present said report at the ensuing annual meeting of the Board with such recommendations as the Committee may deem appropriate.

Nominating Committee

5.11. The Nominating Committee shall consist of the Chairman of the Board of Trustees *ex officio* and, in addition, three Trustees to be elected by the Board by ballot for a term of three years, who shall be eligible for re-election. Any member elected to fill a vacancy shall serve for the remainder of his or her predecessor's term. The Chairman of the Board shall appoint a member of the Committee as Chairman for a term expiring no later than the expiration of his or her term as a member.

5.12. Sixty days prior to an annual meeting of the Board the Nominating Committee shall notify the Trustees by mail of the vacancies to be filled in the membership of the Board. Each Trustee may submit nominations for such vacancies. Nominations so submitted shall be considered by the Nominating Committee, and ten days prior to the annual meeting the Nominating Committee shall submit to members of the Board by mail a list of the persons so nominated, with its recommendations for filling existing vacancies on the Board and its Standing Committees. No other nominations shall be received by the Board at the annual meeting except with the unanimous consent of the Trustees present.

Employee Benefits Committee

5.13. The Employee Benefits Committee shall consist of not less than three and not more than four members to be elected by the Board of Trustees by ballot for a term of three years, who shall be eligible for re-election, and the Chairman of the Finance Committee *ex officio*. Any member elected to fill a vacancy shall serve for the remainder of his or her predecessor's term.

5.14. The Employee Benefits Committee shall, subject to the directions of the Board of Trustees, be responsible for supervision of the activities of the administrator or administrators of any retirement or other benefit plan for staff members and employees of the Institution, except that any matter relating to investments or to the appointment

or removal of any trustee or insurance carrier under any such plan shall be the responsibility of the Finance Committee. It shall receive reports from the administrator or administrators of the employee benefit plans with respect to administration, benefit structure, operation, and funding. It shall consider and recommend to the Board from time to time such measures as in its opinion will improve such plans and the administration thereof. The Committee shall submit a report to the Board at the annual meeting of the Board.

ARTICLE VI

Financial Administration

6.1. No expenditure shall be authorized or made except in pursuance of a previous appropriation by the Board of Trustees, or as provided in Section 5.8 of these By-Laws.

6.2. The fiscal year of the Institution shall commence on the first day of July in each year.

6.3. The Executive Committee shall submit to the annual meeting of the Board a full statement of the finances and work of the Institution for the preceding fiscal year and a detailed estimate of the expenditures of the succeeding fiscal year.

6.4. The Board of Trustees, at the annual meeting in each year, shall make general appropriations for the ensuing fiscal year; but nothing contained herein shall prevent the Board of Trustees from making special appropriations at any meeting.

6.5. The Executive Committee shall have general charge and control of all appropriations made by the Board. The Committee shall have full authority to allocate appropriations made by the Board, to reallocate available funds, as needed, and to transfer balances.

6.6. The securities of the Institution and evidences of property, and funds invested and to be invested, shall be deposited in such safe depository or in the custody of such trust company and under such safeguards as the Finance Committee shall designate, subject to directions of the Board of Trustees. Income of the Institution available for expenditure shall be deposited in such banks or depositories as may from time to time be designated by the Executive Committee.

6.7. Any trust company entrusted with the custody of securities by the Finance Committee may, by resolution of the Board of Trustees, be made Fiscal Agent of the Institution, upon an agreed compensation, for the transaction of the business coming within the authority of the Finance Committee.

6.8. The property of the Institution is irrevocably dedicated to charitable purposes, and in the event of dissolution its property shall be used for and distributed to those charitable purposes as are specified by the Congress of the United States in the Articles of Incorporation, Public Law No. 260, approved April 28, 1904, as the same may be amended from time to time.

ARTICLE VII

Amendment of By-Laws

7.1. These By-Laws may be amended at any annual or special meeting of the Board of Trustees by a two-thirds vote of the members present, provided written notice of the proposed amendment shall have been served personally upon, or mailed to the usual address of, each member of the Board twenty days prior to the meeting.

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A GIFT FOR THE FUTURE OF THE CARNEGIE INSTITUTION OF WASHINGTON

One of the most effective ways of supporting the work of the Carnegie Institution of Washington is to include the Institution in your estate plans. By making a bequest, you can support the Institution well into the future.

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The following sample language can be used in making a bequest to the Carnegie Institution of Washington:

> "I give, and bequeath the sum of $______ (or % of my residuary estate) to the Carnegie Institution of Washington, 1530 P Street, N.W., Washington, DC 20005-1910."

For additional information, please call Susanne Garvey, Director of Institutional and External Affairs, at 202-387-0352, or write:

Susanne Garvey
Director,
Institutional and External Affairs
Carnegie Institution of Washington
1530 P Street, N.W.
Washington, DC 20005-1910